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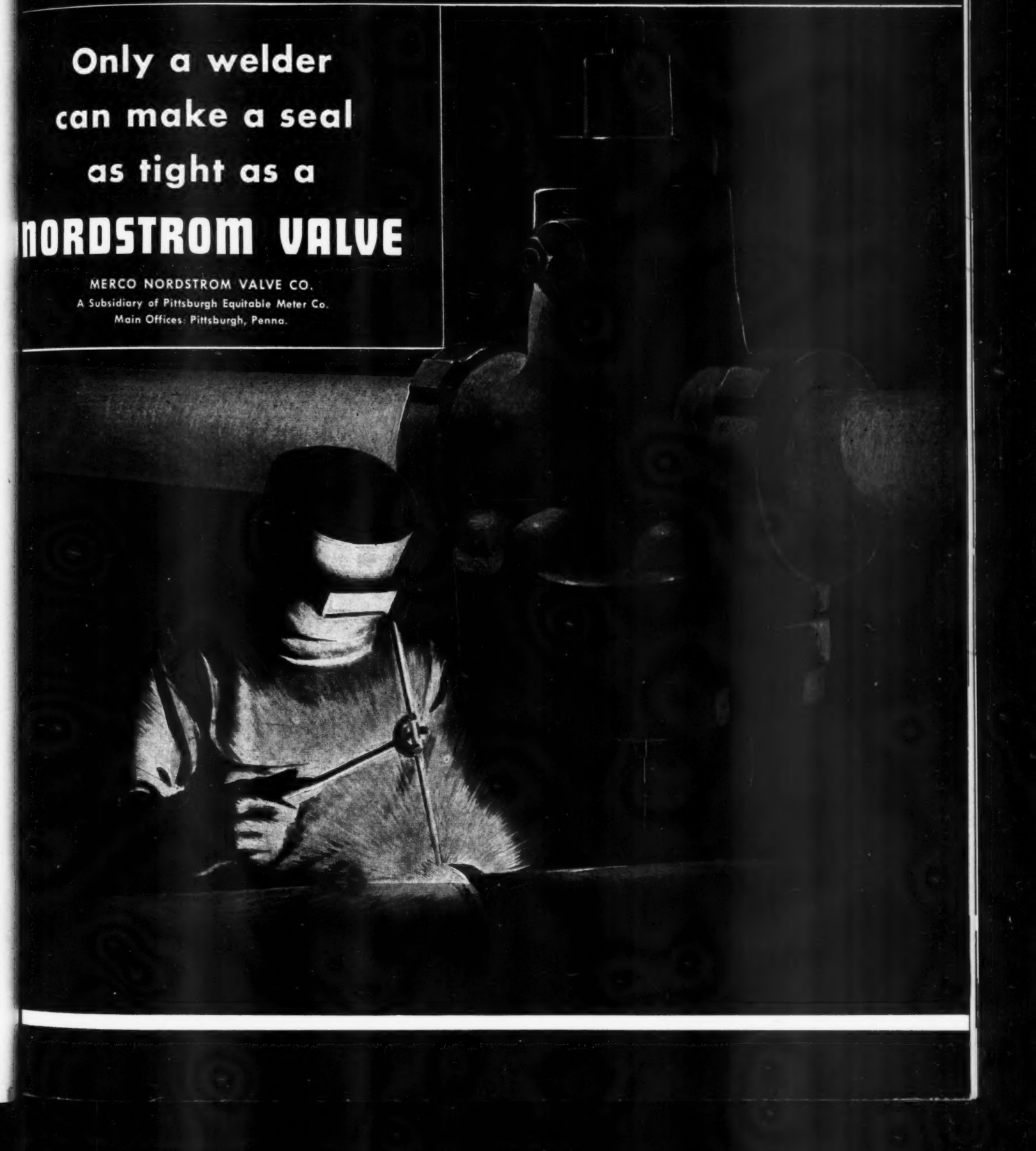

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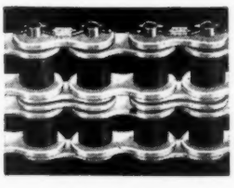

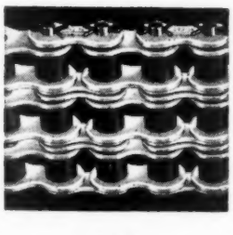

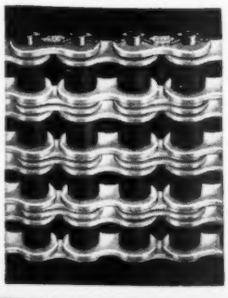

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Annual Number
(July 1, 1941)

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MEMBER A. B. C.—A. B. P. (The articles in *The Petroleum Engineer* are indexed in the *Industrial Arts Index*, New York, N. Y.)

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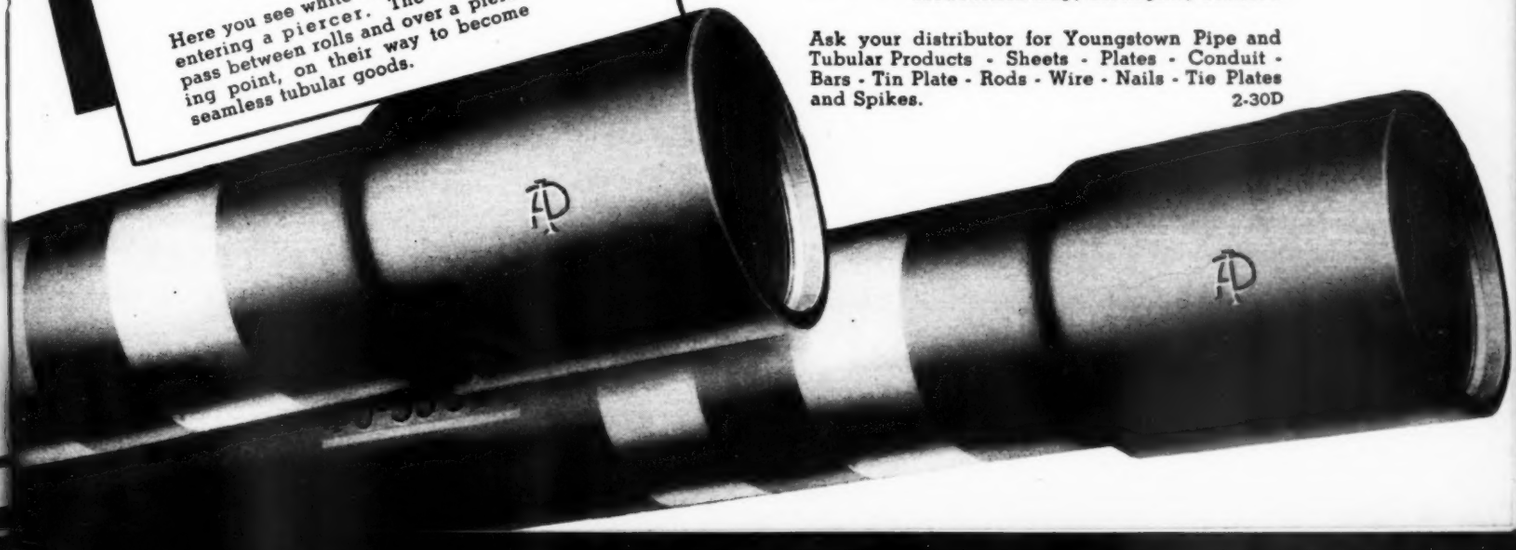


Editorial

An Auspicious Beginning

It has become increasingly clear that Secretary Ickes is genuinely desirous of enlisting the fullest mutual coöperation between the petroleum industry and the government. As Petroleum Coördinator, his opening remarks in addressing the representatives of the petroleum industry at the Conference held in Washington on June 19, left no doubt of his sincere desire for mutual coöperation and a spirit of harmony.

"Your splendid patriotic response to my invitation of only a few days ago demonstrates to me your desire to act for the welfare of the Nation in the common cause. I am deeply gratified by the fact that so large a number of you have subordinated your personal and business interests to the Nation's need and have come here from all parts of the country to take part in this meeting. I am confident too that this auspicious beginning will develop into the most effective program of coöperation between the Nation, the states, and the petroleum industry that our country has ever known.

"Let harmony, coöperation, and a mutual desire and willingness to solve the problems now confronting us be the watchword, not only of this meeting, but of all our future relations."

Mr. Ickes took occasion to point out that, being a coördinator, his policy cannot be one of enforcement; "it is not based on the theory of punitive action, quite the contrary; it is anticipated that the solution of most of our problems will be secured by all parties becoming informed and then working out an agreement to which all parties adhere on the basis of their honor and because of an urge to help defend their country."

Always forthright, Mr. Ickes recognizes the full support and coöperation of the industry with the government as essential in adjusting with dispatch its operations to meet the exigencies of the present National crisis. He said that, "In this effort the oil industry needs the aid of government, and government needs the aid of the oil industry. It is a joint task, a task in which we can acquit ourselves with credit only if we earnestly and harmoniously coöperate; only if we are willing to make the sacrifices that may become necessary."

Ralph K. Davies, Deputy Petroleum Coördinator, in addressing the Conference also emphasized the need for the closest coöperation of the industry with the government when he said, "The stern necessity of accommodating the petroleum resources of the nation to the critical needs of national defense, obviously demands Government coördination. Left to itself there is no way by which the industry can effectively organize its resources and facilities so as to deal, quickly and decisively, with the extraordinary problems of the day. No matter how patriotic and unselfish the component interests and groups within the industry, it is clear that as separate and competing units they cannot act coöperatively, independent of Government direction.

"Government and industry have here a common undertaking. Neither one can act effectively by itself. The demand is for teamwork of the highest order. Only as a joint endeavor, Government and industry coöperating completely, in a mutual undertaking to achieve objectives earnestly desired by both, can genuine success attend these efforts."

Fully alive to the vital need for carrying on normal exploratory operations, and to the prospect of the need for avoiding competitive drilling of unnecessary wells, Deputy Coördinator Davies warned that "perhaps the problem of tomorrow will arise from shortage of vital supplies and services such as steel, skilled labor, machinery, motor transport equipment. Already we face the prospect of limitation upon supplies of steel and other metals and materials. It may be that measures will soon be required to avoid the continued competitive drilling of unnecessary wells in proved fields. If shortage of metals and materials prevents competitive drilling, it is obvious that this, in turn, will require further equitable adjustments between operators in order that the fortunate few may not have an unfair advantage. When we speak of drilling restrictions, however, we must recognize that the search for new fields should be the last activity to be so restricted. Unless the discovery rate is maintained, we shall find ourselves not only depleting reserves, but in the unfortunate position of being compelled to overproduce existing fields with all the waste of oil and gas which that entails." Here Mr. Davies emphasized the importance of conservation: "Important as conservation has been in the past, it is doubly important today." He recognized also the importance of state conservation and stated that "the great reservoir of knowledge and experience of the state conservation authorities will be of great value. The able administration of their respective state conservation laws, directed to the needs of national defense, offers an assurance of good practice and minimum waste in most of the important producing areas. In regions without effective conservation laws, and where good conservation practices are not fully observed, we must seek with you other measures to solve this problem."

Significant were the statements made by Francis Biddle, Acting Attorney General, in addressing the Conference. Any recommendations made with respect to the oil industry, he said, will be scrutinized by his department so that after assurance was given there could be no question that officials in the petroleum industry could carry them out without any fear of feeling that they might run into a snag. "That is essentially important," he said, "so as to have your complete confidence in us, and ours in you."

These assurances to the industry of coördination by mutual coöperation, on the basis of which difficulties will be overcome by mutual agreement rather than by punitive means, mark an auspicious beginning to the petroleum industry's coöperative effort in the National emergency. Let us share the hope with Mr. Ickes that this auspicious beginning will develop into the most effective program of coöperation between the Nation, the states, and the petroleum industry that our country has ever known.

THE Petroleum Engineer

Annual Number

Oil Demand Heavy First Half of 1941—Wildcat Drilling May Show Substantial Gain

PETROLEUM ENGINEER Exclusive Feature

☆ New drilling operations at close of June 27 percent greater than level of preceding year—Refining operations in excess of year ago with runs to stills greatest in history of the industry

by H. J. Struth, Petroleum Economist

THE annual race between oil supply and demand placed demand well in the lead at the halfway mark of 1941.

Transcending all basic economic factors of the petroleum industry's current half year is the realization that stocks of gasoline at the beginning of the heavy summer motoring season actually constitute a supply that is 12 percent below the level of a year ago.

Stocks of gasoline on June 30 were apparently about 8 percent below the volume in storage at this time last year. The record-breaking demand for motor fuel this year, however, has automatically lowered the supply gauge to the point where 100 bbl. of gasoline in storage last year are today equivalent to but 88 bbl. of supply.

Whereas refinery production, imports, and storage carry-over in the first half of this year constituted an increase in gasoline supply of 22,000,000 bbl. over the same period of last year, domestic consumption and exports for the current half year showed an increase over last year of 29,000,000 bbl. A year ago, gasoline stocks constituted 48.2 days' supply; today's gasoline stocks are equivalent to but 42.6 days of supply.

Despite the fact that refining operations showed an increase over last year of 3 percent, storage accumulations of gasoline in the first half of this year aggregated less than 2,500,000 bbl. By comparison, additions to gasoline storage in the corresponding period of last year aggregated more than 11,500,000 bbl.

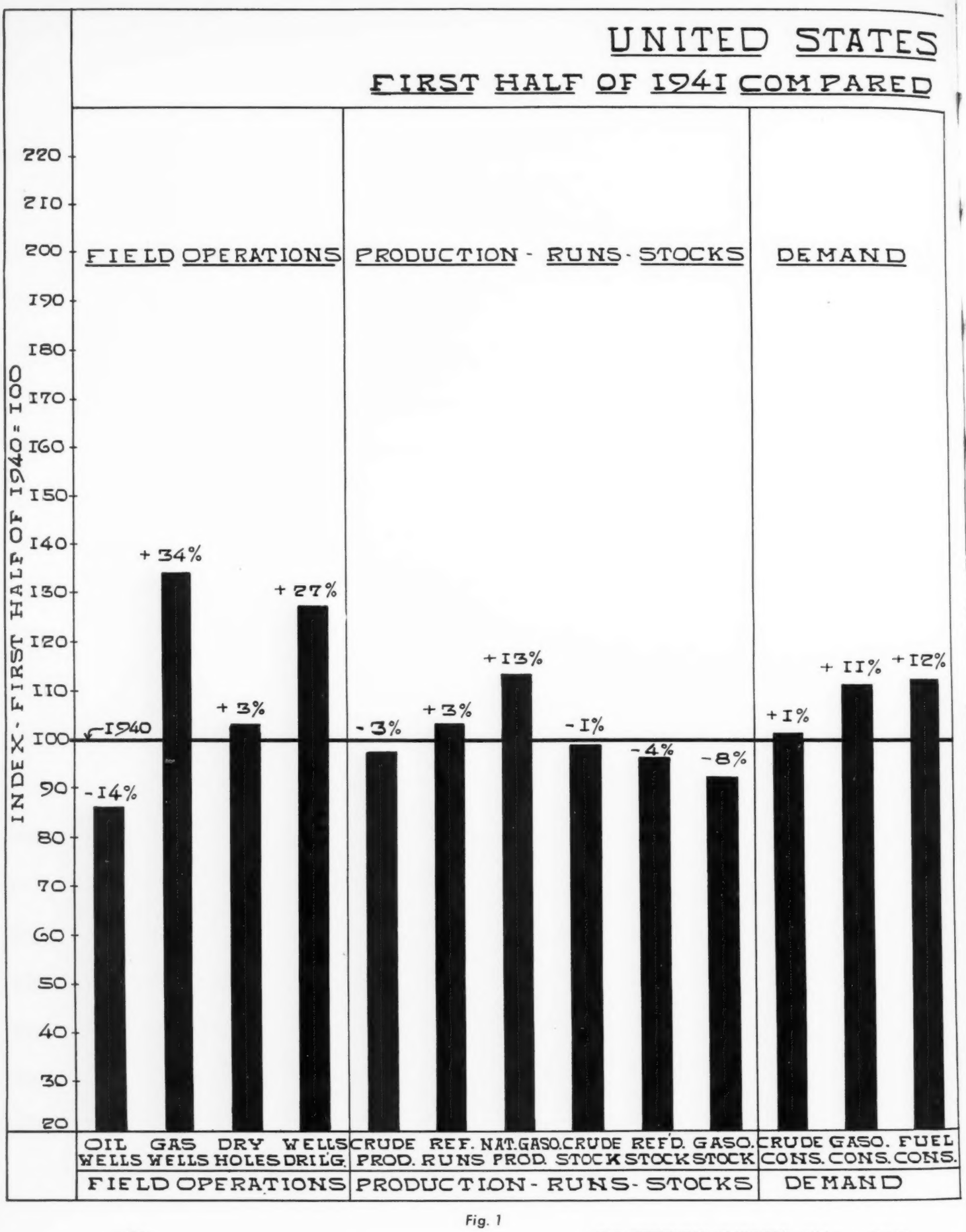
Runs to Stills High

Currently, refining operations are 6 percent greater than a year ago and runs to stills are now at the highest level in the history of the industry. Gasoline stocks cannot be considered inadequate by any means, particularly in the light of existing productive facilities and readily available supplies of crude oil. Yet, the fact remains that supplies of gasoline are inadequate on the East Coast—or will be shortly—as a result of the transfer to Britain of 55 coastwise tankers.

The "shortage" of gasoline on the East Coast presents a problem to the industry at this time, particularly when the national demand for motor fuel is greater than ever before. The curtailment of exports to Axis-controlled nations and the speeding-up and rerouting of remaining water transportation facilities should, how-

H. J. STRUTH

has been analyzing economic conditions of the petroleum industry for more than two decades—He will be eligible for membership in the Twenty-five Year Club next year—Is a member of the Petroleum Division of the American Institute of Mining and Metallurgical Engineers and has contributed many valuable economic papers to the oil and gas industry—He was formerly chairman of economics of the A.I.M.E. and was recently made a member of the Minerals Economics Committee of the Institute—Struth was publisher of Petroleum Economic Service at Houston, Texas, when he was called to Washington to serve as technical adviser to the Petroleum Administrative Board, in the early days of the N.R.A.—Is now economist for the Texas Mid-Continent Oil and Gas Association, Dallas, Texas, having served in that capacity for the last 6 years.


UNITED STATES
FIRST HALF OF 1941 COMPARED
INDEX - FIRST HALF OF 1940 = 100
220
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200
190
180
170
160
150
140
130
120
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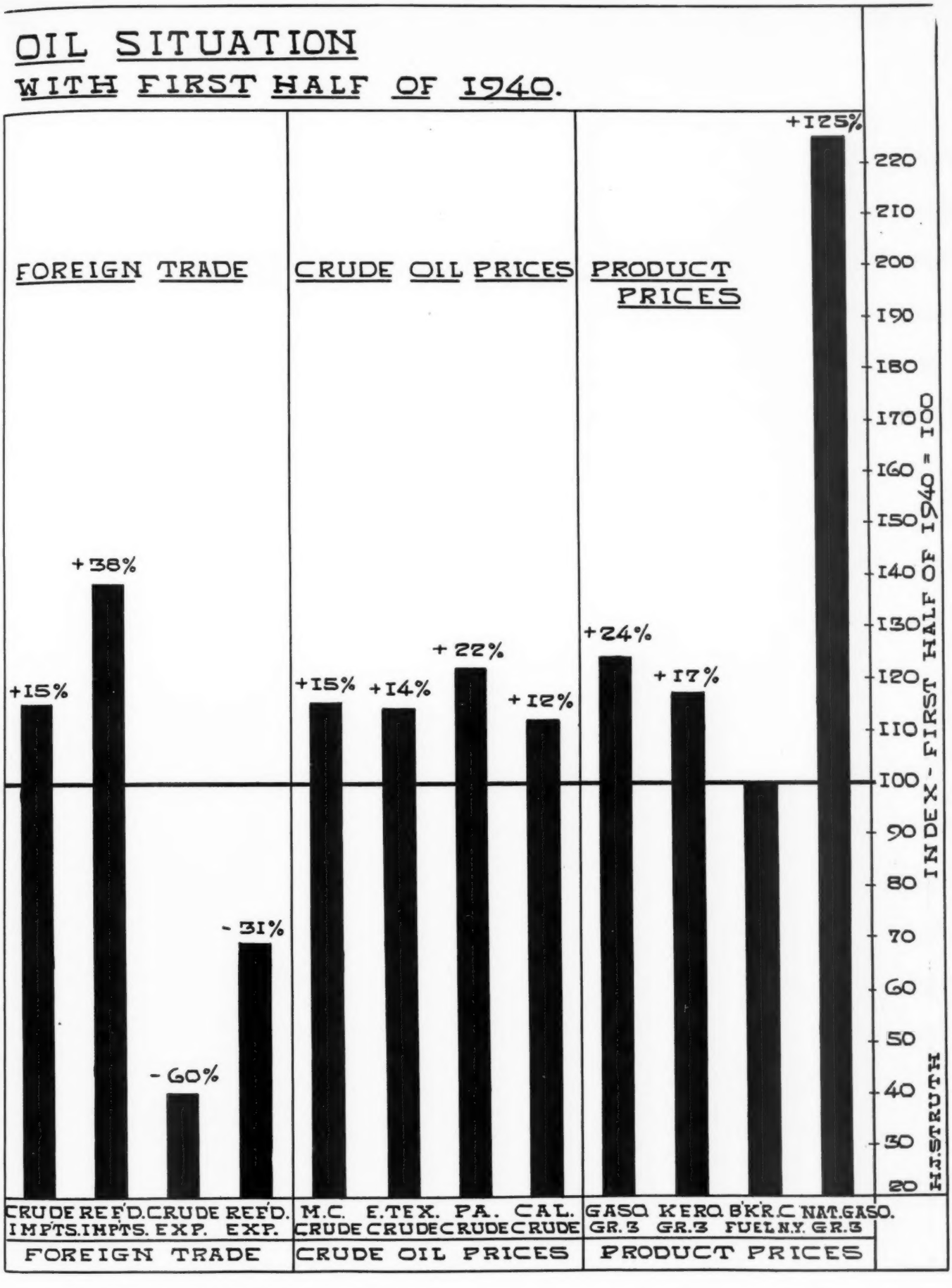
100
90
80
70
60
50
40
30
20
FIELD OPERATIONS
PRODUCTION - RUNS - STOCKS
DEMAND
1940
-14%
+34%
+3%
+27%
-3%
+3%
+13%
-1%
-4%
-8%
+1%
+11%
+12%
OIL WELLS
GAS WELLS
DRY HOLES
WELLS DRILG.
CRUDE PROD.
REF. RUNS
NAT. GASO. PROD.
CRUDE STOCK
REF'D. GASO. STOCK
GASO. STOCK
CRUDE CONS.
GASO. CONS.
FUEL CONS.
FIELD OPERATIONS
PRODUCTION - RUNS - STOCKS
DEMAND

Fig. 1


OIL SITUATION
WITH FIRST HALF OF 1940.
FOREIGN TRADE
CRUDE OIL PRICES
PRODUCT PRICES
+15%
+38%
-60%
-31%
+15%
+14%
+22%
+12%
+24%
+17%
+125%
INDEX - FIRST HALF OF 1940 = 100
220
210
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HJ.STRUTH
CRUDE IMPTS.
REF'D. IMPTS.
CRUDE EXP.
REF'D. EXP.
M.C. CRUDE
E.TEX. CRUDE
PA. CRUDE
CAL. CRUDE
GASO GR.3
KERO GR.3
B'KR.C FUEL N.Y.
NAT.GASO. GR.3
FOREIGN TRADE
CRUDE OIL PRICES
PRODUCT PRICES

ever, go a long way toward the alleviation of the temporary "shortage." Meanwhile, it is likely that definite plans will take shape for the building of national defense pipe lines from the Gulf Coast to the Atlantic Seaboard.

Refining operations in the Indiana-Illinois and Appalachian areas are being stepped-up to provide additional gasoline supplies for the East Coast area. In the first half of the year Indiana-Illinois refining operations were increased nearly 10 percent above this time last year, and Appalachian plants ran greater than 4 percent more crude than at this time last year. All refining areas with the exception of Oklahoma recorded increased runs of crude oil in the first half of this year.

Industry Condition Better

Statistically, the petroleum industry is in better condition than it has been for a number of years. The chart of 25 basic petroleum industry factors (Fig. 1) shows how the various indices of demand have outdistanced the supply factors in the first half of this year, compared with the same period of last year. The effect of this favorable statistical picture is reflected by the lifting of the industry's entire price structure from levels that have for some time been considered inadequate.

AS is our custom, editorial features such as *The Petroleum Engineer's* Continuous Tables," "Laugh With Barney," "Major Refining Activities," "Highlights in Oildom," etc., are omitted from this Annual Number. These features will appear as usual in the regular July issue and each issue thereafter.

TABLE I
UNITED STATES PETROLEUM SITUATION
First half of 1941 compared with first half of 1940

	First half 1940	First half 1941*	Index 1940–100	Percent change
Total wells drilled	14,968	13,838	92	— 8
Oil wells drilled	10,903	9,370	86	— 14
Gas wells drilled	929	1,246	134	+ 34
Dry holes drilled	3,136	3,222	103	+ 3
Percent dry holes	20.9	23.4	....	+ 2.5
Wells drilling (June 30)	3,796	4,825	127	+ 27
Crude oil production	687,901,000	666,750,000	97	— 3
Daily average	3,780,000	3,683,000		
Refinery crude runs	645,408,000	666,987,000	103	+ 3
Daily average	3,546,000	3,685,000		
Natural gasoline production	26,341,000	29,750,000	113	+ 13
Daily average	145,000	164,000		
Crude oil stocks:				
January 1	252,240,000	275,985,000		
June 30	275,305,000	272,500,000	99	— 1
Change	+23,065,000	—3,485,000		
Days supply (June 30)	71.3	68.0	95	— 5
Gasoline stocks:				
January 1	81,722,000	83,647,000		
June 30	93,276,000	86,030,000	92	— 8
Change	+11,554,000	+2,383,000		
Days supply (June 30)	48.2	42.6	88	— 12
All refined oils:				
January 1	268,109,000	282,265,000		
June 30	283,905,000	274,300,000	96	— 4
Change	+15,796,000	—4,965,000		
Days supply (June 30)	82.0	76.0	93	— 7
Total crude demand	682,978,000	690,661,000	101	+ 1
Daily average	3,752,000	3,816,000		
Domestic gasoline consumption	278,622,000	309,568,000	111	+ 11
Daily average	1,531,000	1,710,000		
Domestic fuel consumption	253,944,000	285,700,000	112	+ 12
Daily average	1,395,000	1,578,000		
Imports:				
Crude oil	18,142,000	20,426,000	113	+ 13
Daily average	100,000	115,000		
Refined oils	20,516,000	28,312,000	138	+ 38
Daily average	113,000	156,000		
Total imports	38,658,000	48,738,000	126	+ 26
Daily average	213,000	269,000		
Exports:				
Crude oil	26,415,000	10,617,000	40	— 60
Daily average	145,000	59,000		
Refined oils	43,716,000	30,135,000	69	— 31
Daily average	240,000	165,000		
Total exports	70,131,000	40,752,000	58	— 42
Daily average	385,000	224,000		
Crude oil prices:	June 30, 1940	June 30, 1941		
Mid-Continent, 36 gravity	$1.02	$1.17	115	+ 15
East Texas	1.10	1.25	114	+ 14
Pennsylvania, National Transit	2.25	2.75	122	+ 22
California, Signal Hill 26	.99	1.11	112	+ 12
Refinery Product Prices:	June 30, 1940	June 30, 1941		
U. S. Motor Gasoline, Gr. 3	4⅝	5¾	124	+ 24
U. S. Motor—Gulf	4¼	5½	129	+ 29
U. S. Motor—New York	6	7¾	129	+ 29
U. S. Motor—California	5	5¾	115	+ 15
Natural Gasoline, Gr. 3	1⅛	3⅝	225	+125
Natural Gasoline, California	5¼	4½	86	— 14
Kerosine, 41-43, Gr. 3	3¾	4⅜	117	+ 17
Kerosine—New York	5⅜	5¼	96	— 4
Bunker C. fuel, New York	$1.35	$1.35	100	0
Furnace Oil, No. 1, Gr. 3	3⅜	3⅞	115	+ 15
Bright Stock, Pennsylvania No. 1	19½	23½	121	+ 21

*Preliminary—subject to revision.

Although curtailment of crude oil production by the leading "Compact States" during the first half of this year cannot fail to have had a favorable influence upon the supply and demand picture, the fact remains that the demand exceeded all expectations and thus created a far more favorable statistical picture than might have been realized had the demand actually experienced been fully anticipated.

The only factors opposing the otherwise favorable situation are those of foreign trade, where supply greatly exceeded demand. The increase in oil imports and the sharp drop in exports created an equivalent outside crude oil supply of at least 25,000 bbl. per day in the first half of this year.

Last year, even though export trade had already been sharply reduced, the net effect of our foreign trade—imports and exports—was to create an additional demand for domestic crude oil of more than 200,000 bbl. per day.

Field Operations

The effect of a rising price structure upon the industry's field operations is shown by comparing field operations for the first half of this year with those of June. In the first half of the year drilling operations were off 8 percent from last year. In June, just ended, well completions were only 3 percent under a year ago. It is likely that drilling operations of the current month will increase substantially above the level of last year.

Drilling operations usually conform to the rise and fall of oil prices. Table 1 and the Petroleum Situation Chart (Fig. 1) show that new drilling operations at the close of June were 27 percent greater than the level of the preceding year. Numerous wildcat operations were begun after the recent crude price advances and it is evident

now that drilling operations over the remainder of this year will show a material gain over results recorded for the first half.

The completion of more than 300 additional gas wells this year, mostly in the Appalachian area, caused the gas well index to rise 34 percent above the first half of last year. The sharp increase in gas well drilling activity, coupled with more wildcat drilling in the first half of the year, contributed to the increase of 2½ percent in dry wells to total wells completed.

TABLE 2
OIL SUPPLY AND DEMAND PICTURE FOR JUNE
June, 1941, compared with June, 1940
(All figures on U. S. Bureau of Mines basis)

	June, 1940	June, 1941*	Percent change
Total wells drilled	2,768	2,700	— 3
Daily crude production	3,723,000	3,796,000	+ 2
Daily refinery runs	3,608,000	3,837,000	+ 6
Daily natural gasoline production	147,000	173,000	+18
Daily crude consumption	3,839,000	3,976,000	+ 4
Daily gasoline consumption (domestic)	1,849,000	2,016,000	+ 9
Daily fuel oil consumption (domestic)	1,069,000	1,385,000	+30
Daily imports, all oil	222,000	280,000	+25
Daily exports, all oil	474,000	200,000	—58

*Preliminary—subject to revision.

Refining Operations

The rise in refining operations to new high levels in June has also had a material effect upon the demand for crude oil. Table 2 presents a preliminary summary of basic facts for June, which are graphically portrayed in Fig. 2. Although the demand for crude oil in the first half of this year showed an increase over last year of only 1 percent, the preliminary data for June indicate a gain over a year ago of 4 percent.

If the movement of gasoline to the Eastern Seaboard can be accelerated sufficiently to avert curtailment of private use, it is likely that domestic gasoline consumption for the full year will show an increase over 1940 of at least 12 percent. This is considerably greater than earlier forecasts indicated.

The sharp rise in demand for motor fuel and aviation gasoline this year has been a boon to the natural gasoline manufacturers. Production of natural gasoline showed an increase over last year of 15 percent, boosting the daily output 19,000 bbl. over the first half of last year.

Production statistics for June show that the output of natural gasoline increased 26,000 bbl. per day, bringing the production level 18 percent greater than a year ago.

Heavy industrial demand for fuel oil this year resulted in an increase in domestic demand compared with last year of 12 percent. This topped the percentage gain recorded by the domestic demand for motor fuel.

On the basis of increased demand for petroleum products already recorded and in prospect this year, it is conservatively estimated that the demand for domestic crude oil for all of 1941 will show a net increase over 1940 of at least 150,000 bbl. per day.

Fig. 2

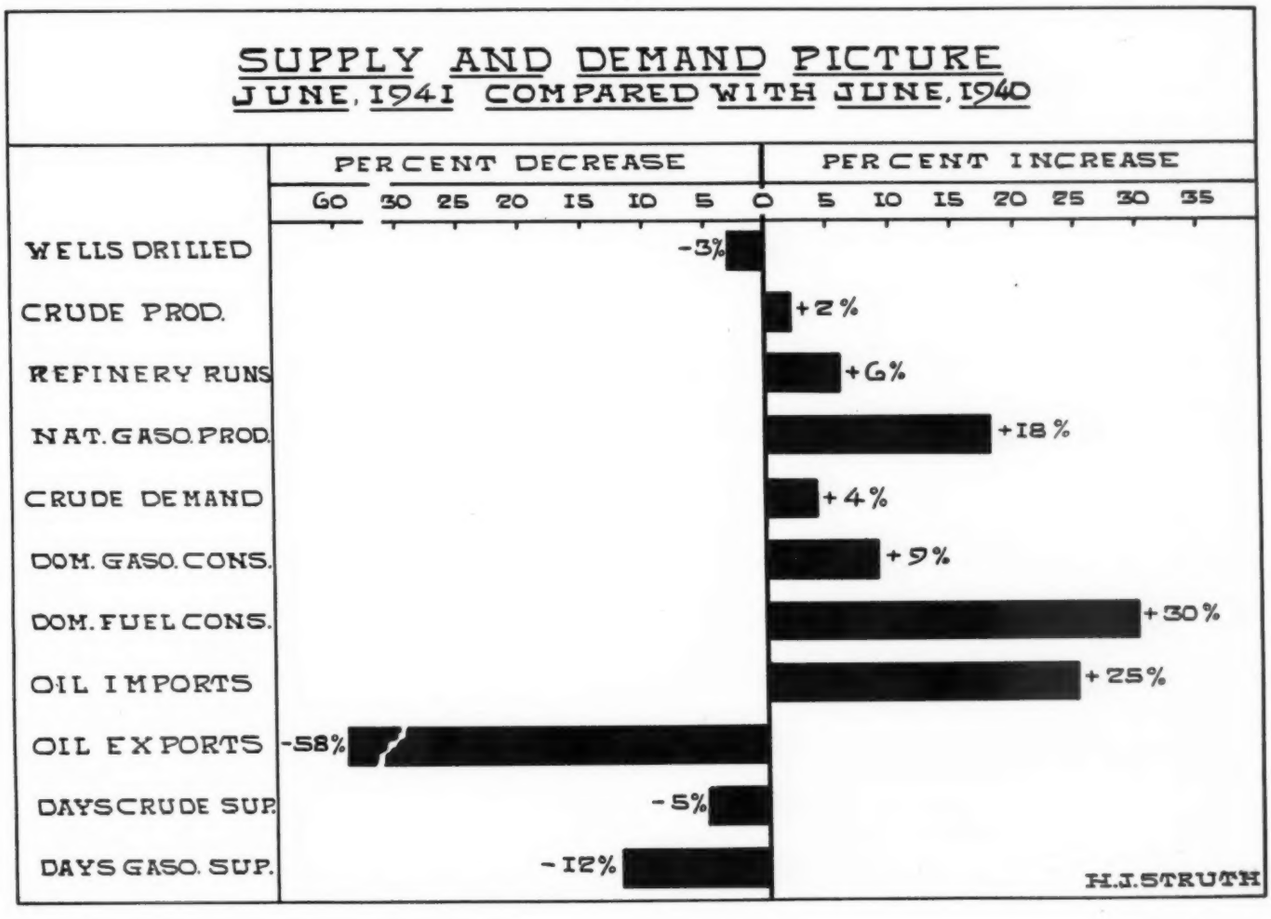


TABLE 3
RATIO OF GASOLINE TO CRUDE OIL
Mid-Continent Area

	Price of 36 Gr. crude oil at wells	Refinery price of U. S. Motor gasoline—Gr. 3 (cents per gal.)	Ratio gasoline to crude oil
January, 1929	$1.36	8.33	16.3
June, 1929	1.45	9.25	15.7
January, 1930	1.45	6.92	21.0
June, 1930	1.29	6.25	20.6
January, 1931	0.95	3.35	28.3
June, 1931	0.33	3.54	9.3
January, 1932	0.77	3.81	20.2
June, 1932	0.88	4.03	21.8
January, 1933	0.69	2.57	26.8
June, 1933	0.44	4.69	9.4
January, 1934	1.00	4.47	22.4
June, 1934	1.00	4.40	22.7
January, 1935	1.00	4.22	23.7
June, 1935	1.00	5.51	18.1
January, 1936	1.00	6.01	16.6
June, 1936	1.10	5.75	19.1
January, 1937	1.10	5.94	18.5
June, 1937	1.22	5.70	21.4
January, 1938	1.22	5.10	23.9
June, 1938	1.22	4.96	24.6
January, 1939	1.02	4.64	22.0
June, 1939	1.02	5.10	20.0
January, 1940	1.02	4.51	22.6
June, 1940	1.02	4.50	22.7
January, 1941	1.02	4.50	22.7
June, 1941	1.17	5.75	20.3

Stocks

Under existing emergency conditions, it would appear sound to increase above-ground stocks of crude oil and also to maintain gasoline and distillate fuel oil stocks at reasonably higher levels. It should be borne in mind that the expected increase in crude oil demand this year of 150,000 bbl. per day provides for no additions to existing inventories, either of crude oil or refined products.

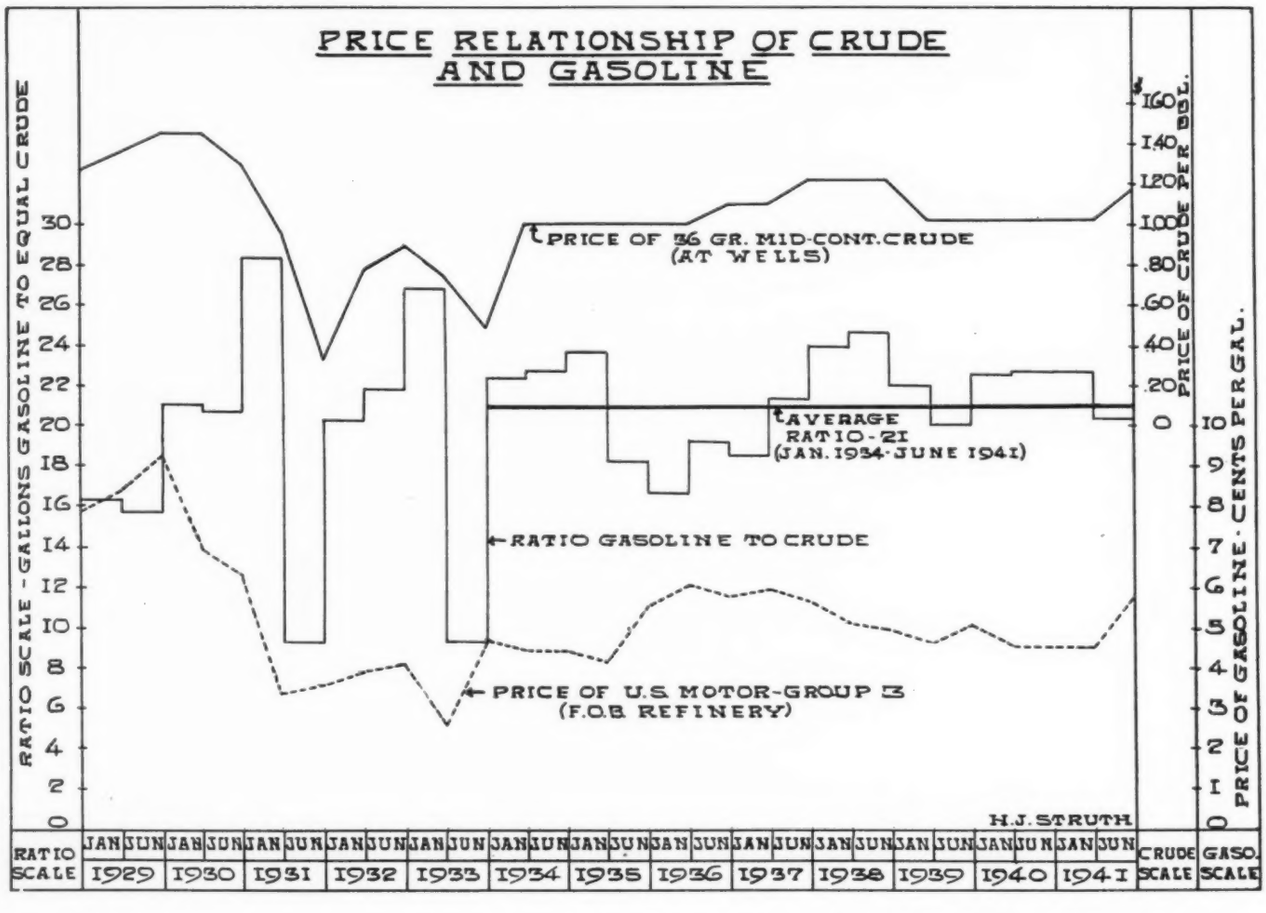
In the first half of this year crude oil stocks were reduced to the extent of nearly 3,500,000 bbl. In the same period of last year, crude oil stocks were increased more than 23,000,000 bbl. On the basis of June demand for crude oil, stocks on June 30 constituted 68 days' supply, which is equivalent to a 5 percent reduction from the preceding year.

Another significant development of the first half of this year is the fact that stocks of all refined products were reduced nearly 5,000,000 bbl., whereas in the first half of last year product stocks increased more than 15,000,000 bbl. On a days supply basis, current stocks of refined products are actually 7 percent below the level of last year.

Prices Advanced

Rising prices of crude and refined products have on the whole been justified by the favorable change in the oil industry's statistical position. Crude oil prices were advanced an average of 11 percent in the first half of this

Fig. 3


PRICE RELATIONSHIP OF CRUDE AND GASOLINE
RATIO SCALE - GALLONS GASOLINE TO EQUAL CRUDE
PRICE OF CRUDE PER BBL.
PRICE OF GASOLINE - CENTS PER GAL.
PRICE OF 36 GR. MID-CONT. CRUDE (AT WELLS)
AVERAGE RATIO - 21 (JAN. 1934 - JUNE 1941)
RATIO GASOLINE TO CRUDE
PRICE OF U.S. MOTOR-GROUP 3 (F.O.B. REFINERY)
H.J. STRUTH
RATIO SCALE
CRUDE SCALE
GASO. SCALE
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year whereas refinery product prices rose on an average of about 22 percent above the levels prevailing a year ago.

The fact that crude oil production and refinery processing of crude had not actually paced the unprecedented increase in demand for petroleum products has been a contributing factor in the underlying strength displayed in both the crude oil and refinery market structures.

Increased demand for natural gasoline, spurred by greatly increased use of motor fuel this year, has corrected the market inequalities that prevailed in the natural gasoline price structure a year ago. Unwieldly stocks of both natural gasoline and motor fuel last year depressed prices of natural gasoline to an extremely low level. Liquidation of stocks and a generally improved statistical position in motor fuel and natural brought prices in line with other refined products, but it took an increase of 125 percent from a year ago to do it.

A study of price ratios of Mid-Continent refinery gasoline to the posted price of 36-gravity Mid-Continent crude during the last 12 years reveals the fact that the present price scales of $1.17 for crude and 5¾ cents for U. S. motor gasoline in Group 3 are close to parity.

Over the last 8 years, the average ratio of refinery gasoline to crude has been 21. In other words, it has taken an average of 21 gal. of refinery gasoline to equal the posted price of crude oil. At the close of June, the ratio of gasoline to crude was 20.3. On the average ratio of 21, therefore, the present price of gasoline would justify $1.21 for crude—or, if crude were used as the base, gasoline should sell for about 5⅝ cents per gal. at the refinery.

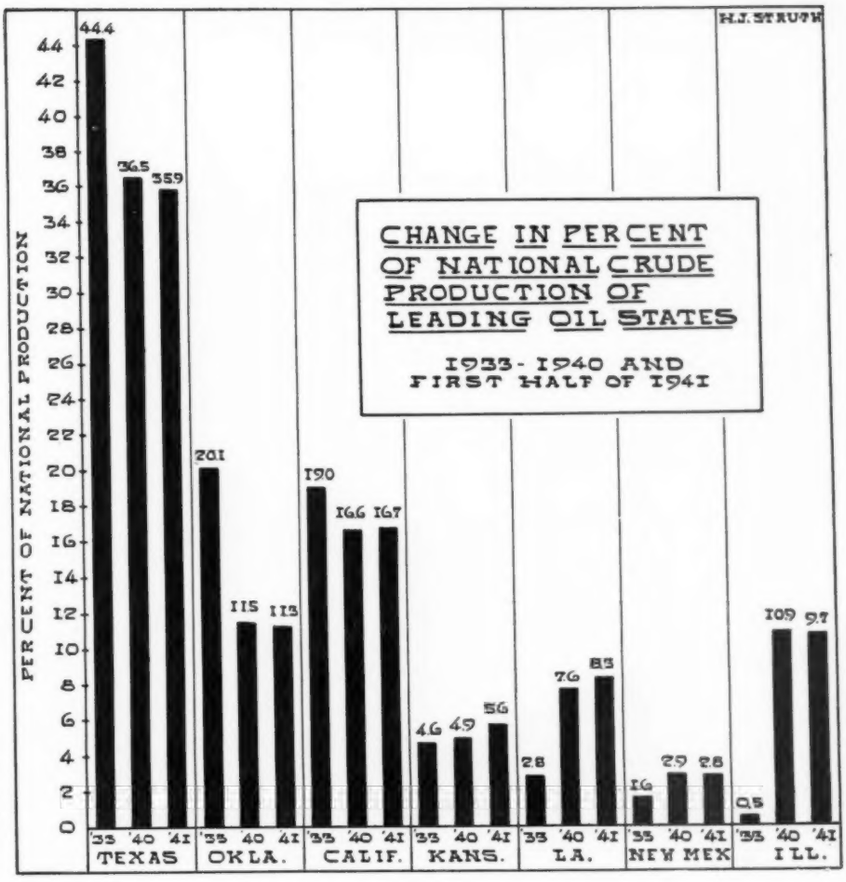


Fig. 4

Stabilization and Fluctuation

The results of this study are shown in Table 3 and the accompanying chart (Fig. 3). It is interesting to note how crude oil and gasoline prices have become stabilized since 1934, in comparison with the wild gyrations that prevailed between 1929 and 1934. The writer is not advocating here that the oil industry should adopt a definite gasoline price ratio of 21 to crude, but merely attempts to show the actual relationship that has existed between Mid-Continent crude oil and gasoline during the last 12 years.

It is also interesting to compare price relationships of crude oil and gasoline prior to 1934. Between 1929 and 1934 the average ratio of gasoline to crude in Group 3 was about 18.5. Price fluctuations during that period, however, resulted in ratios ranging from a high of 28.3 to a low of 9.3.

Similar comparisons between gasoline and crude oil in other areas reveal relationships somewhat in conformity with the picture shown for the Mid-Continent area. If we use Signal Hill 26-gravity crude in California as a base, the ratio of refinery gasoline to crude oil becomes 19.5 compared with the June ratio in the Mid-Continent area of 20.3.

The price ratio picture in Pennsylvania cannot readily be compared with other areas because crude oil prices there are based primarily upon the market value of bright stocks. On June 30, the ratio of bright stock to Pennsylvania crude oil stood at 11.7. This is based upon the latest quotation on bright stock of 25½ cents per gal. and related to the current posted price of Bradford crude oil of $2.75 per bbl.

The division of the national market for crude oil among the various oil-producing states has undergone some important changes during the last 8

TABLE 4
PERCENTAGE OF NATIONAL CRUDE OIL PRODUCTION BY STATES

	1933	1940	January-June 1941*	Change from 1933
Texas	44.4	36.5	35.9	— 8.5
Oklahoma	20.1	11.5	11.3	— 8.8
Kansas	4.6	4.9	5.6	+ 1.0
New Mexico	1.6	2.9	2.8	+ 1.2
Louisiana	2.8	7.6	8.3	+ 5.5
Illinois	0.5	10.9	9.7	+ 9.2
California	19.0	16.6	16.7	— 2.3
Other states	7.7	9.1	9.7	+ 2.0
Total	100.0	100.0	100.0	....

*Preliminary—subject to revision.

TABLE 5
PROVED OIL RESERVES PER WELL
January 1, 1941

	Producing wells	Oil reserves, million bbl.	Reserves per well, bbl.
Texas	95,214	10,624	111,580
Oklahoma	54,587	1,002	18,356
Kansas	20,673	692	33,474
New Mexico	3,396	692	203,769
Louisiana	6,208	1,215	195,715
Illinois	20,227	315	15,573
California	15,059	3,291	218,404
Other states	166,350	1,194	7,178
Total	381,714	19,025	49,841

years. In 1933, Texas, Oklahoma, and California produced 83.5 percent of the nation's oil supply. In the first six months of this year these three states produced but 63.9 percent of the nation's oil, a net loss of markets of nearly one-fifth.

Table 4 and the accompanying chart (Fig. 4) show how the market for crude oil has changed since 1933 among the leading oil-producing states. Texas and Oklahoma have suffered severe losses in their markets for crude, which are shown to have been shifted to new supply sources in Kansas, Louisiana, and Illinois.

Preliminary production figures by states for the first half of this year, compared with the same period of last year, show that crude production of Texas and Oklahoma dropped 21,000,000 bbl. Coincidentally, this was the exact amount of the total reduction in crude oil production under the first half of last year. Other states east of the Rocky Mountains and exclusive of Texas and Oklahoma scored a combined net gain in production in the first half of this year of 1,000,000 bbl.

Although Illinois has been a factor of major importance in the shifting of markets for crude oil, the fact remains that production of this state in the first half of this year showed a net decline of more than 13,000,000 bbl. from last year. This indicates what happened when the peak of flush production had been passed. Kansas, Louisiana, Arkansas, California and the Eastern States outside of Illinois showed a combined net increase in production during this period of 14,000,000 bbl.

Reserves

The soundest argument in favor of conservation is to cite the effect of unrestricted production in Illinois in comparison with conditions prevailing in Texas, under strict conservation laws. With reserves in Illinois computed at 315,000,000 bbl., production of that state in 1940 aggregated nearly 147,000,000 bbl. At this rate, Illinois produced 466 bbl. of oil for each 1000 bbl. of proved reserves underground.

By comparison, Texas has more than 10,500,000,000 bbl. of reserves and produced last year 493,000,000 bbl. of crude oil. Thus, Texas produced but 46 bbl. of oil for each 1000 bbl. of underground reserves. Illinois, therefore, is using her reserves more than 10 times as fast as Texas!

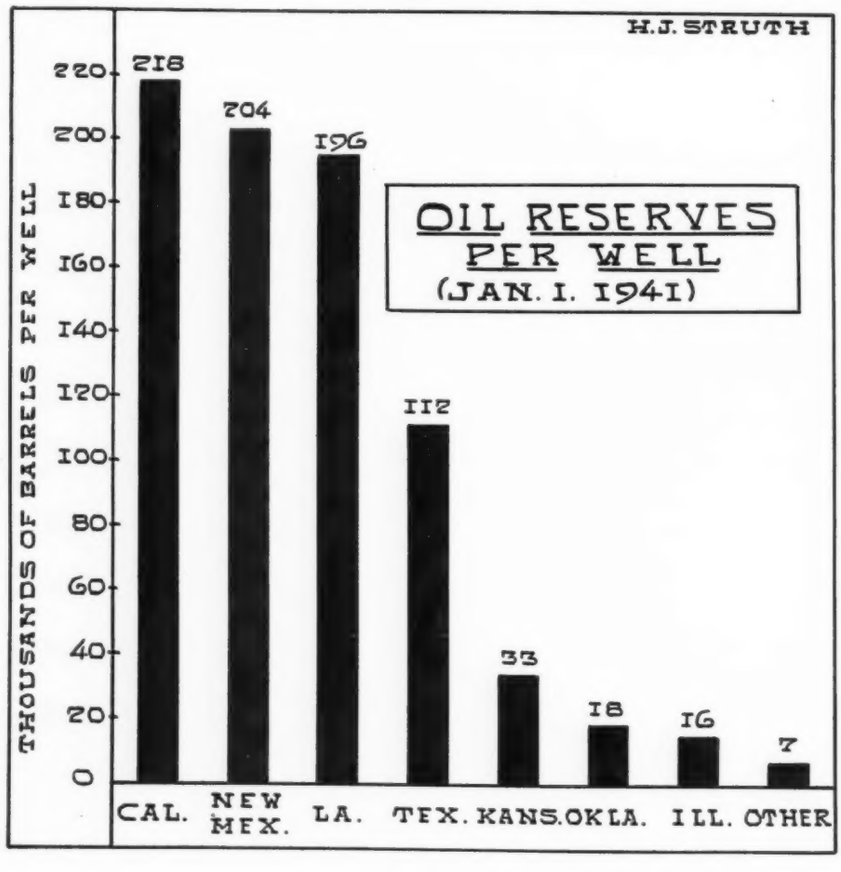
Despite the fact that California's oil field developments have not resulted in the discovery of substantial new sources of potential oil supply, that state holds the leadership in the amount of unproduced oil reserves available per producing well. At the beginning of this year, California was credited with total proved reserves of 2,291,000,000 bbl., and had on January 1 a total of 15,059 producing oil wells. It is evident, therefore, that California has reserves averaging more than 218,000 bbl. per well.

New Mexico holds second place with more than 205,000 bbl. per well; Louisiana holds third place with more than 195,000 bbl. per well, and Texas is fourth with an average of 111,000 bbl. of reserves per producing well.

Although Texas has more than 53 percent of the nation's proved oil reserves and has twice as much unproduced oil as the other three leading oil states combined, it has more than 95,000 producing oil wells. The number of producing wells in Texas is roughly four times as great as the other three states combined.

These figures are of particular importance at this time as they provide a reliable index of the nation's dependable sources of immediate and future oil supply both for national defense and civilian needs.

Fig. 5



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Planning for Flexibility in Selecting Subsurface Lifting Equipment[1]

PETROLEUM ENGINEER Exclusive Feature

☆ Objective in Placedo field, Texas, is to progress from (1) flowing to (2) natural intermittent flow to (3) open gas-lift to (4) closed gas-lift operation with minimum equipment and labor

by Paul F. Barnhart

District Engineer, Barnsdall Oil Company

PRODUCTION in the Placedo field, Victoria County, Texas, is from the Greta sand at a depth of approximately 4770 ft. First completion in this sand was in June, 1935. The Greta sand is divided into different thin producing sand sections by shale and hard sandy limestone beds. The thin producing sand sections of the Greta sand are known as the Smith Stringer, First Shaly, and White sand. Some wells are completed from only the Smith Stringer sand section, which is approximately 1 to 3 ft. thick, and is the uppermost of the several producing sections. Some of the wells are completed with the casing set through from the First Shaly sand, which is approximately 13 ft. thick, whereas some are producing from both the Smith Stringer and First Shaly sands. Other wells are completed in the White sand, which is the lowest producing section of the Greta sand and has a maximum vertical saturation of approximately 30 ft. on the crown of the structure.

The White sand is the cleanest and possesses the highest productivity. Very thin but relatively clean, the Smith Stringer sand possesses in some wells a productivity almost equal to that of the White sand. A dirtier sand than either the Smith Stringer or White sands, the First Shaly sand, possesses a lower productivity. The gas-oil and oil-water contacts are common to these three sections.

Generally speaking, the Greta sand in this field is considered a dirty, shaly, bentonitic, loose, and unconsolidated sand. This is exemplified by the fact that it has been impossible to complete any wells satisfactorily in the Greta sand by setting casing through the sand and perforating. The method of completion involves open hole with a screen liner set opposite the sand. The shaly condition of the sand varies in different sections of the field and quite often varies in offset wells. The separate producing sand sections, the variation in shale conditions, and permeability all result in marked differences of the productivity of each well. The productivity indexes of the gas-lift wells vary from approximately 0.1 to 0.5 bbl. per day per lb. sand face differential.

The gravity of the crude oil produced is 25.5° A.P.I. The initial bottom-hole pressure was apparently normal for this area and was estimated to be approximately 2170 lb. per sq. in. A gas cap is present over the dome of the structure and the sand possesses a water drive. There are approximately 150 producing wells in the field. Barnsdall Oil Company owns and operates about one-third of these wells.

When Barnsdall was originally considering artificial recovery methods, gas-lift appeared to be the most economical procedure of artificial lift. This determination was based on consideration of a number of conditions, one of the most important being the ideal availability of gas requirements. The source of the gas had previously been found by wells completed as gas wells in a deeper sand, which possesses more than adequate reserve, pressure, and volume requirements. Another factor considered was that the Greta sand wells occasionally produce sand in sufficient volume to cause them to become plugged. Gas-lift presents the easiest method of artificially producing fluid containing sand. When wells become sanded-up it has quite often proved more economical to clean-out the sand by gas-lift. Considering the availability and economical source of gas, the high fluid levels, the apparent water drive, and other factors, indications were that gas-lift appeared to be the most economical method of artificial lift.

In the latter part of 1937 and early part of 1938, it was necessary to equip the majority of the wells for gas-lift. At that time salt water was being produced by most of these wells to a small extent. The productivity indexes of the wells, considering bottom-hole pressure decline and rate of increased water production, made it apparent that gas-lift by open systems could

PAUL F. BARNHART

attended Texas A. and M. College and University of Oklahoma—Received a B.S. degree in petroleum engineering from the latter in 1937—Was employed by Public Service Corporation of Mississippi in 1931-32 assisting in surveying, construction and maintenance work of gas pipe-line and distribution systems—Roughnecked in East Texas field summer 1934—Employed by Barnsdall Oil Company as roustabout July, 1936, in Oklahoma City field—Worked in production department until transferred to Gulf Coast and South Texas district October, 1937, as district engineer—For last 3¾ years has assisted in supervising the drilling and completing of more than 80 wells in numerous fields of the Gulf Coast and South Texas, as well as assisted in handling production problems of some 180 wells in this area.

[1]This article is an outgrowth of material orally presented at a conference on gas-lift held at Texas A. and M. College.

profitably be employed for at least two years before it would probably be necessary to resort to more efficient gas-lift depletion methods. At that time gas-lift by the closed system had been used very little. Flow valves were installed, therefore, in the wells in the Placedo field with open systems. The spacing of the top valves utilized an available kick-off pressure of approximately 900 lb. per sq. in. and the lower valves were set to open under a 100-lb. differential pressure. Spacing between valves was determined by the accepted manner of dividing the opening differential pressure of the flow valve by the fluid pressure gradient per foot to determine the distance between valves. The bottom valves were so spaced from bottom that sufficient tail pipe was present to prevent blowing around the bottom of the tubing with the operating casing pressures employed.

From early 1938 to the first part of 1940, gas-lift with flow valves was employed with open systems. Production was easily obtained at first but subsequent operation indicated that it would be necessary to resort to more efficient gas-lift methods in order to produce the wells to depletion. In the latter part of 1939 increased water production, decreased bottom-hole pressures, and low productivity of the wells indicated that to produce the wells efficiently to depletion would require installing closed systems in nearly all the wells. Some of the lower productivity wells needed closed systems at that time in order to reduce the bottom-hole operating pressures required in open-system operation. This was necessary in order to increase fluid production and obtain the allowed oil production.

From test data it was known that the productivity of most of the wells would require operating with a maximum sand face differential or a minimum bottom-hole operating pressure, considering the increased water production obtained, in order to produce these wells to depletion by gas-lift. It had also been found from experience that the productivity index of a well would sometimes change as a result of sand trouble. It was therefore believed important to equip these wells with closed systems in such a manner that gas-lift could be performed by automatic flow valve operation at any working fluid level, and also with surface-controlled wire-line installations, if needed, in order to employ gas-lift economically.

Fig. 1 shows the installation adopted as a standard in equipping the wells for closed system gas-lift. It was believed this installation would serve to produce each well to depletion, even though later changes might be necessary in methods of gas-lifting by closed system before reaching abandonment. Fig. 1 shows the tubing equipped with automatic flow valves spaced to kick-off and automatically operate at any depth depending upon the desired production, productivity of the well, and employing optimum pressures and volumes of input gas. The lower end of the tubing is equipped with a control head packer and standing valve. Immediately above the packer is a fluid bypass seating chamber. In Fig. 1, a removable drop valve is shown seated in the seating chamber. This removable drop valve is not installed until needed, however, as herein later described. When kicking-off or unloading a well, this fluid bypass seating chamber provides a bypass for the fluid from the annulus into the tubing as would be obtained in an open system. Experience in unloading gas-lift wells on closed systems has proved the importance of employing a means of transferring the fluid from the annular space with minimum effort. If the desired production is obtainable by operating from an automatic flow valve at a fluid level above the seating chamber, thus maintaining a fluid seal in this bypass seating chamber, then the removable drop valve need not be installed in the seating chamber until later.

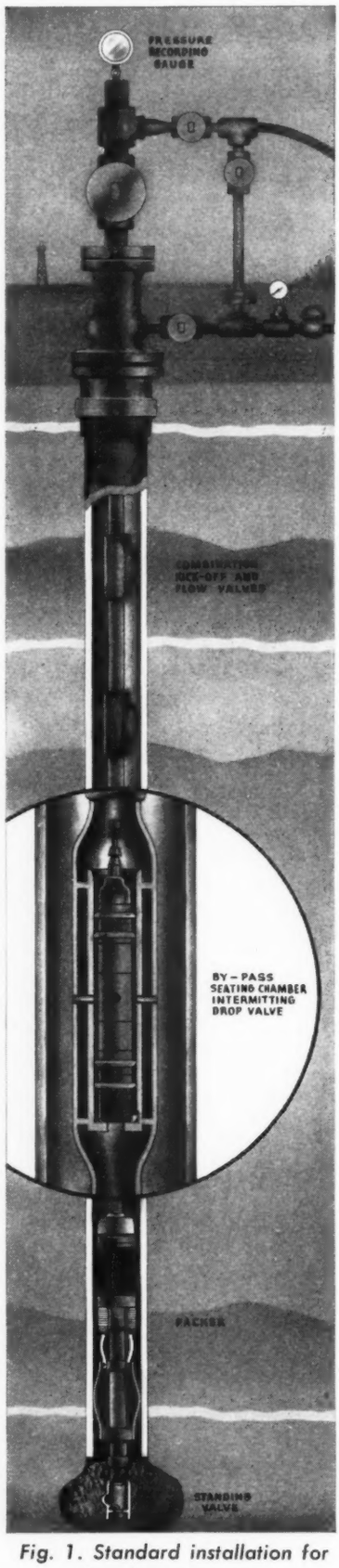


Fig. 1. Standard installation for closed system gas-lift

This seating chamber provides facilities for gas-lift operation until low productivity, reduced bottom-hole pressure, and increased water production require operation with as little back pressure opposite the sand face as possible. This change may be made without the necessity of changing the gas-lift installation or equipment except for purchasing and installing the removable drop valve equipped with an automatic intermitting valve.

Fig. 2 shows the removable drop valve equipped with a center-section for automatic intermitting valve operation. This drop valve is installed in the seating chamber after unloading the well down to the seating chamber. It is run on a measuring line with short stroke jars and set in the seating chamber with the jars, which also shears a pin releasing the running-in tool from the drop valve. In most of the gas-lift wells it has been necessary to operate with a lower bottom-hole pressure than that employed when intermitting automatically from flow valves above the seating chamber. In some of these wells the drop valve has been installed with the automatic intermitting valve center section in place. This allows the well to operate automatically at a maximum depth, and reduces the bottom-hole operating

pressure at the sand face to a minimum. The maximum bottom-hole operating pressure is then equivalent to the applied casing pressure opposite the drop valve, less the opening differential of the flow valve and plus the back pressure in the tubing.

This standard closed system installation also provides means of employing gas-lift during the latter period of a well's life. This is accomplished by installing a wire-line surface-controlled installation, still without abandoning any part of the previous system or without pulling the tubing. It is only necessary to purchase and install the necessary surface equipment. The drop valve shown in Fig. 2 is removed from the seating chamber by a measuring line and jars, and the automatic flow valve center section is replaced by a surface-controlled wire-line operating valve as shown in Fig. 3. The drop valve is then again set in the seating chamber by means of the measuring line. It may be seen from Fig. 2 that the top of the drop valve is equipped with a plunger. This plunger is depressed by means of a wire-line weight bar to open the valve causing gas to be injected into the tubing for periods of time the length and frequency of which are surface-controlled.

To amplify the distinction between a surface-controlled wire-line installation and an automatic operating flow valve that is producing from a maximum depth, the wire-line unit permits lower bottom-hole operating pressure to be imposed by virtue of decreasing the fluid weight or height of fluid required to open an automatic flow valve, which will in turn increase production. The limit of reduction is reached, however, when the minimum submergence results in excessive gas-fluid ratios. To explain this in another manner, if the automatic flow valve used in the drop valve requires an opening differential pressure of 125 lb. and the casing pressure opposite this valve is 500 lb. for efficient lift, a 375-lb. head of fluid, less back pressure, must be built-up above the automatic valve before the valve will open to admit the injection gas. With a surface-controlled wire-line installation, the fluid above the wire-line valve can be ejected from the tubing when any desired fluid volume has accumulated, thus imposing a smaller operating pressure against the formation and resulting in greater production.

Fig. 4 shows the surface equipment that is purchased and installed when equipping the well for surface-controlled wire-line intermitting. The equipment includes a hydraulic piston to which the wire line and weight bar are attached, an automatic time-cycle controller, small reducing regulator, and a wire-line stuffing box. The hydraulic piston is operated by gas pressure and the automatic time-cycle controller permits the gas pressure to raise and lower the piston at desired periods. Only additions to the subsurface equipment are the wire line and weight bar, together with the center section of the drop valve changed for surface-controlled wire-line operation. All previously purchased equipment is still used, and the surface-controlled wire-line installation is completed without the necessity of pulling tubing.

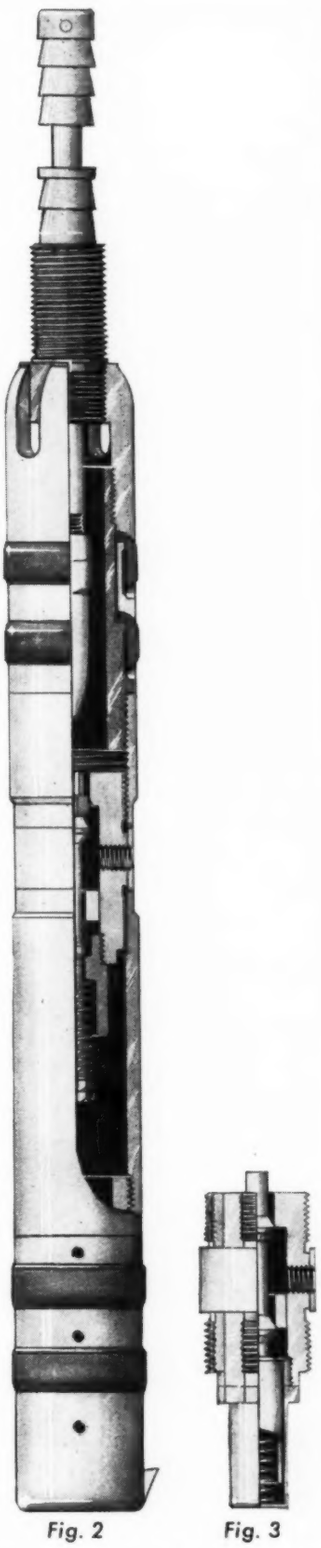


Fig. 2 Fig. 3

Fig. 2. "Drop valve" equipped with automatic intermitting flow valve center section. Fig. 3 shows the center section of the "drop valve" for surface controlled wire-line operation

Pressure Bomb Indicates Source of Trouble

A number of bottom-hole pressure bomb tests have been made to determine static fluid levels or maximum bottom-hole pressures, productivity indexes of wells, and to ascertain the cause for inefficient operations in some wells. The bottom-hole pressure bomb has aided in determining leaks in the tubing through which gas was escaping, leaking valves above the intermitting valve in operation, and the operating depth of the automatic intermitting valve. A change in productivity has been noted by means of the pressure bomb in a well where sand trouble was encountered.

Some problems were, of course, encountered in working out efficient operation of the closed systems in the various wells. It was found necessary in one well to employ a 2-in. full-opening flapper check valve for the standing valve in the bottom of the tubing in order to prevent plugging from foreign matter. It was found advantageous to run a perforated basket on a measuring line when the tubing was out of the hole to clean the well of foreign material floating or in suspension in the fluid.

Control head packers were used on the bottom of the tubing as it was believed that this type of packer could more easily be removed from a well having a high fluid level or from one that had sanded up. Two production-type packers, which do not have the control head feature or fluid bypass through the packer, were used for experimentation. They were used in 7-in. O.D. and 9⅝-in. O.D. casing. Both of these wells later sanded-up, making it difficult to pull the packers. Experience has proved in this field that control-head packers are justifiable.

When considering gas-lift as a method for depleting this field to abandonment, numerous other factors that affect efficient gas-lift were considered and corrected to the extent that was economically possible. The gas wells were equipped with 1000-lb. (working

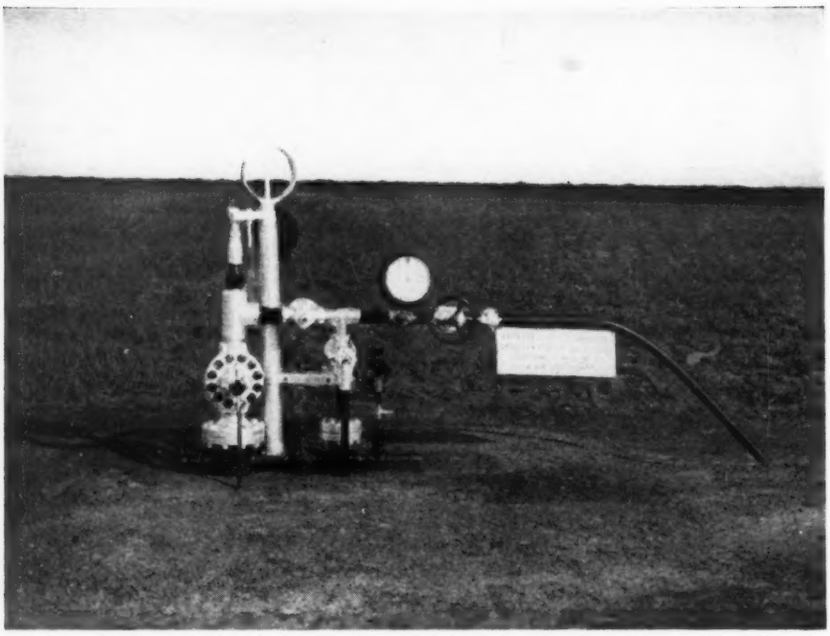


Fig. 4. Christmas tree showing surface equipment installed for wire-line operation

pressure) separators and pilot-operated regulators in order to maintain a constant pressure of approximately 900 lb. per sq. in. on the gas lines in the field. An orifice meter was installed at each gas well to measure all gas used. The gas pipe-line system was designed to deliver adequate pressures and volumes to the various gas-lift wells in the field. On all gas-lift wells, with the exception of the surface-controlled wire-line installations, individual 1000-lb. per sq. in. (working pressure) regulators were installed on the gas line entering the casing of each well. Because of the varying well conditions, individual regulation of input pressure for each well is required with automatic flow valve operation to attain efficient gas-lifting.

It is quite important to reduce the back pressure on the gas-lift wells to a minimum to aid in obtaining maximum production with efficient gas-lift operation. In this connection the flow lines from the Christmas trees were streamlined by salvaging choke body and other fittings to eliminate all 90-deg. bends between the wellhead and the separator. This also required streamlining the headers ahead of the separators at the tank batteries. This was accomplished by providing sufficiently large piping where needed to prevent excess friction from large fluid volumes.

In some cases it was necessary to shorten flow lines and build additional tank batteries. It is important in this connection to select proper size separators to handle maximum expected production with a minimum required operating pressure. The back-pressure maintained at the discharge of the eductor is the unconsumed energy not employed for performing work in gas-lifting. Increased back pressures result in decreased gas-lift efficiencies. The ft-lb. of energy expended in reducing the pressure of a cu.ft. of gas from 50 lb. per sq. in. gauge to atmospheric pressure is equivalent to the ft-lb. of energy expended in reducing the pressure of a cu. ft. of gas from 600 to approximately 125 lb. per sq. in. It is obvious, therefore, that it is important to have a minimum back pressure at the wellhead in order to utilize all the available energy in the gas for gas-lifting.

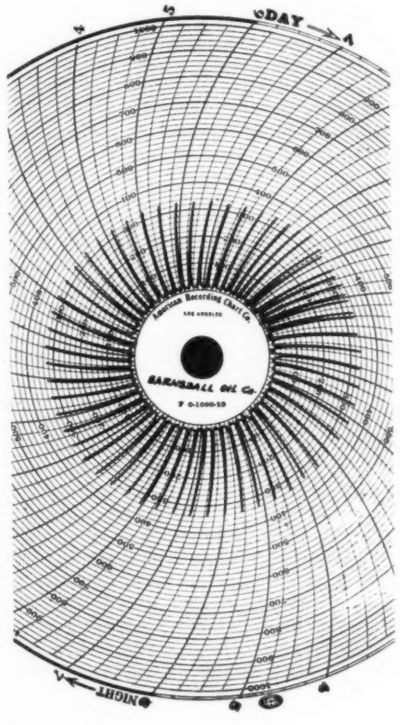
Each gas-lift well is equipped with a 24-hr. recording pressure gauge on the tubing. These charts give evidence of intermitting valve performance, as may be seen from Fig. 5. Such charts are delivered to the field office each morning and should the predetermined, regulated, daily well production not be obtained, these charts are used in determining the corrective measures to be applied.

Barnsdall has approximately 30 closed-system installations in the Placedo field. There are approximately 20 drop valves installed in these wells, and the other wells are still operating automatically above the seating chamber essentially as open systems. Some of these drop valves have been in service more than a year. A number of the wells have been pulled and repaired during that time because of cutting-out, and for the purpose of changing port sizes for volume requirements when needed. By virtue of the drop valve installations, tubing jobs have not been required. Four wire-line surface-controlled installations are also installed and are giving satisfactory operation on low productive wells.

Conclusion

It has been found from tests that input gas-fluid ratios vary from 225 to 800 cu. ft. per bbl., depending upon well productivity and whether operating conditions are favorable or unfavorable. The calculated efficiency of lift, when determined, was approximately 22 percent, which may be considered satisfactory performance. The lift efficiency was calculated by determining the ft-lb. of work performed in lifting a barrel of fluid, of known specific gravity, a given vertical distance, and dividing by the actual work developed during isothermal expansion of the gas used at given pressure in actually performing this work.

Fig. 5. Recorded pressure gauge chart illustrating intermitting valve performance



Piling Substructure For Open-Water Drilling Location In Gulf

PETROLEUM ENGINEER Exclusive Feature

Heavy steel beams connect piling, resulting in more uniform distribution of load

by I. W. Alcorn

Chief Petroleum Engineer,
Gulf Coast Producing Division, Pure Oil Company

SUBSTRUCTURES for derrick and machinery are formidable items entering into the cost of drilling operations in open waters of the Gulf of Mexico. As regards the design of such structures, local conditions must be taken into account, but experience is also a very desirable aid in arriving at a suitable and economical design.

Such experience with similar structures was an important factor governing the design of a piling substructure for a well 9000 ft. offshore in about 18 ft. of water (mean low tide) at an open-water location in the Creole Area, Cameron Parish, Louisiana, on the Gulf of Mexico.

The entire substructure and the arrangement of all machinery and equipment thereon were developed largely from experience gained on a combination barge and piling substructure used on an inland-water location in the Louisiana Gulf Coast.[1]

For the piling structure under discussion, the design called for the use of a Diesel-electric drilling rig consisting of two 350-hp. Diesel engines connected to a common generator.

Instead of mounting the power machinery on a barge, as was done on the location just referred to,[1] the derrick, power machinery, mud pumps, and tanks are all mounted on a piling structure, as shown in the accompanying drawing on page 32. All piling is driven to a penetration of 30 ft. and connected by heavy steel beams instead of the conventional timber capping. As all the piles are interconnected by bolted steel beams, each pile carries a uniform part of the load. Uniform distribution of the load among the piles by the use of steel beams is the desirable feature that permits an economical design.

Under the derrick structure there are 34 piles: four under each corner on 8-ft. centers, two on each side, four under the rotary table, 2 under the drawworks, and 4 under the standby engine and drawworks. These are 70-ft. southern pine, creosoted (16-lb. treatment) piles with 8-in. points and 16½-in. butts. The piling arrangement is shown in the accompanying drawing. The four piles under the rotary table have 6-ft. centers, and the four piles under standby engine and drawworks are driven on 9-ft. by 12-ft. centers. The height of the derrick floor above mean water level is approximately 32 ft.

Heavy steel I-beams, 36-in., 240-lb., of wide flange section, cap the derrick piling. These are surmounted by cross beams of similar weight and cross-section as shown in the drawing.

In the substructure carrying the engines, mud pumps, and tanks, there are 75 piles. These are of southern pine, creosoted (16-lb. treatment). The piles under the mud pumps have 16½-in. butts, all the rest have 14½-in. butts.

I. W. ALCORN

was born September 5, 1899, at Marietta, Ohio —Has received degrees in mining engineering from the Missouri School of Mines, Rolla, Missouri, and Massachusetts Institute of Technology —Began career in oil industry with Independent Oil and Gas Company—Later served on staffs of Smith Separator Company and Oil Well Supply Company—Employed by Pure Oil Company in November, 1935 — Elected first president Houston Technical Club, organized in 1938.

All the derrick piling is sturdily braced and cross-braced with heavy angle-iron bracing. Similarly, the piling under the machinery, mud pumps, and tanks is steel capped and tied-in with 16-in., 40-lb., wide flange steel I-beam members, and sturdily braced and cross-braced with angle-iron bracing. Steel I-beams, 18-in., 17-lb., of wide flange section, are used as intermediate stringers between the main members. The arrangement of piling bracing and steel beams are shown on the accompanying drawing.

One outstanding advantage of the steel beams that cannot be over-emphasized is that the load is uniformly distributed among the piles, thus the service of each pile is utilized to the utmost. Another advantage is that the steel beams have a high—almost 100 percent—salvage value. Already one set of such steel beams has been used on seven different wells. This is an important consideration, particularly should a dry hole result, for the steel beams and decking can be salvaged for use elsewhere.

The cost of this piling substructure is about 50 percent of that of the original structure[2] from which this design was evolved.

All the machinery, including the water tank, reserve mud tanks, mud pump, suction and mixing tanks, and the Diesel-electric units, are compactly arranged on the lower deck. An upper deck extending more than halfway of the machinery piling structure carries the mud house and pipe rack. Experience with the pipe rack on an upper deck has been quite satisfactory.

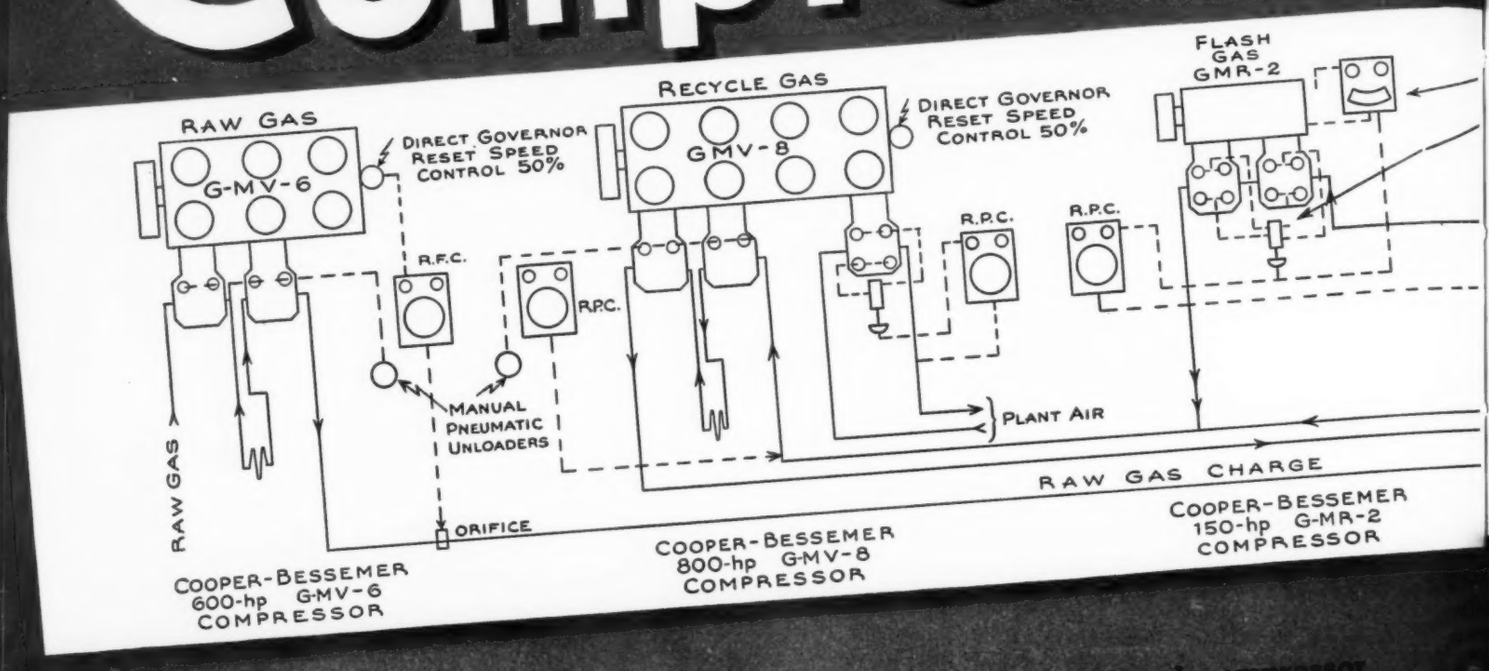
Should the well be a producer, two or more wells may be directionally drilled from one location. On the other hand, should a dry hole result, all steel beams and decking can be salvaged for use at another location.

[1] "Drilling-Rig Layout for Water Locations in the Gulf Coast," by I. W. Alcorn. *The Petroleum Engineer*, April, 1940.

[2] "Derrick Structures for Water Locations," by I. W. Alcorn. *The Petroleum Engineer*, March, 1938.

(For drawing accompanying this article see page 32)

Here's Compressor



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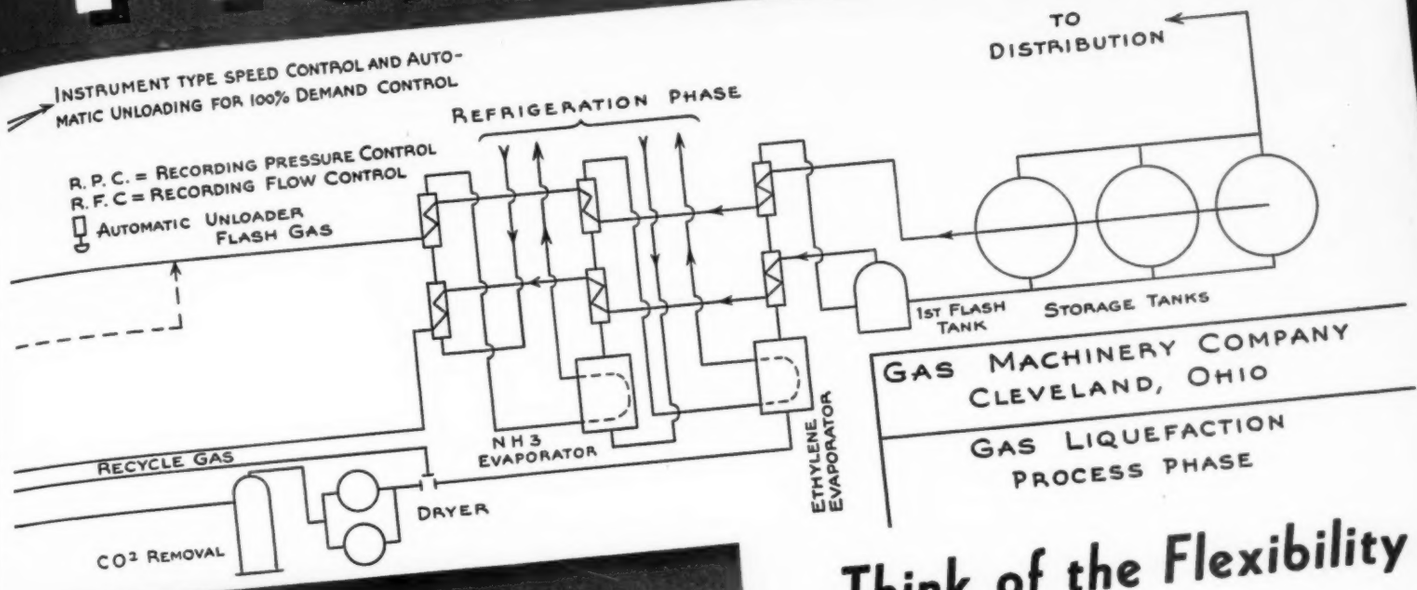

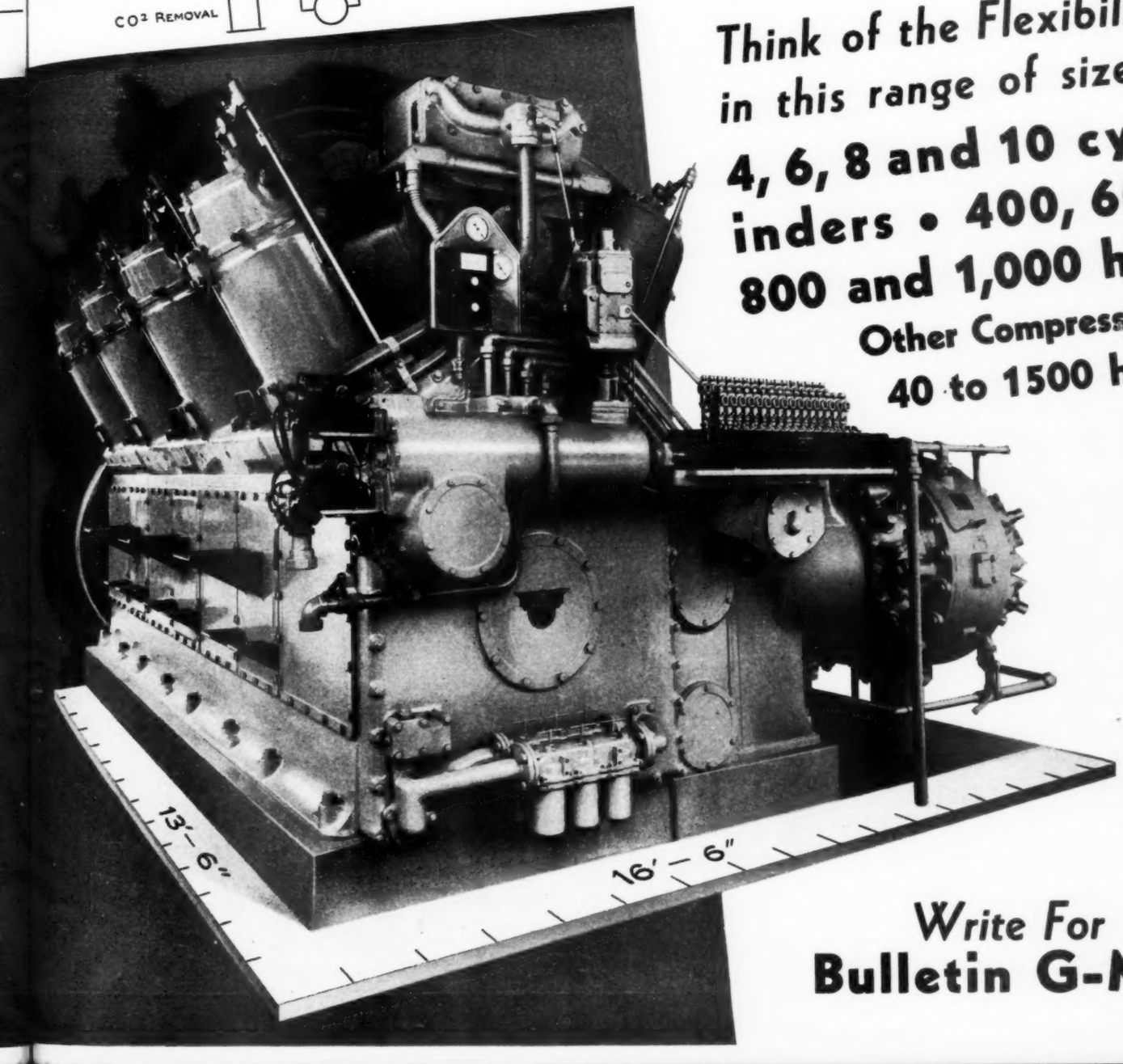

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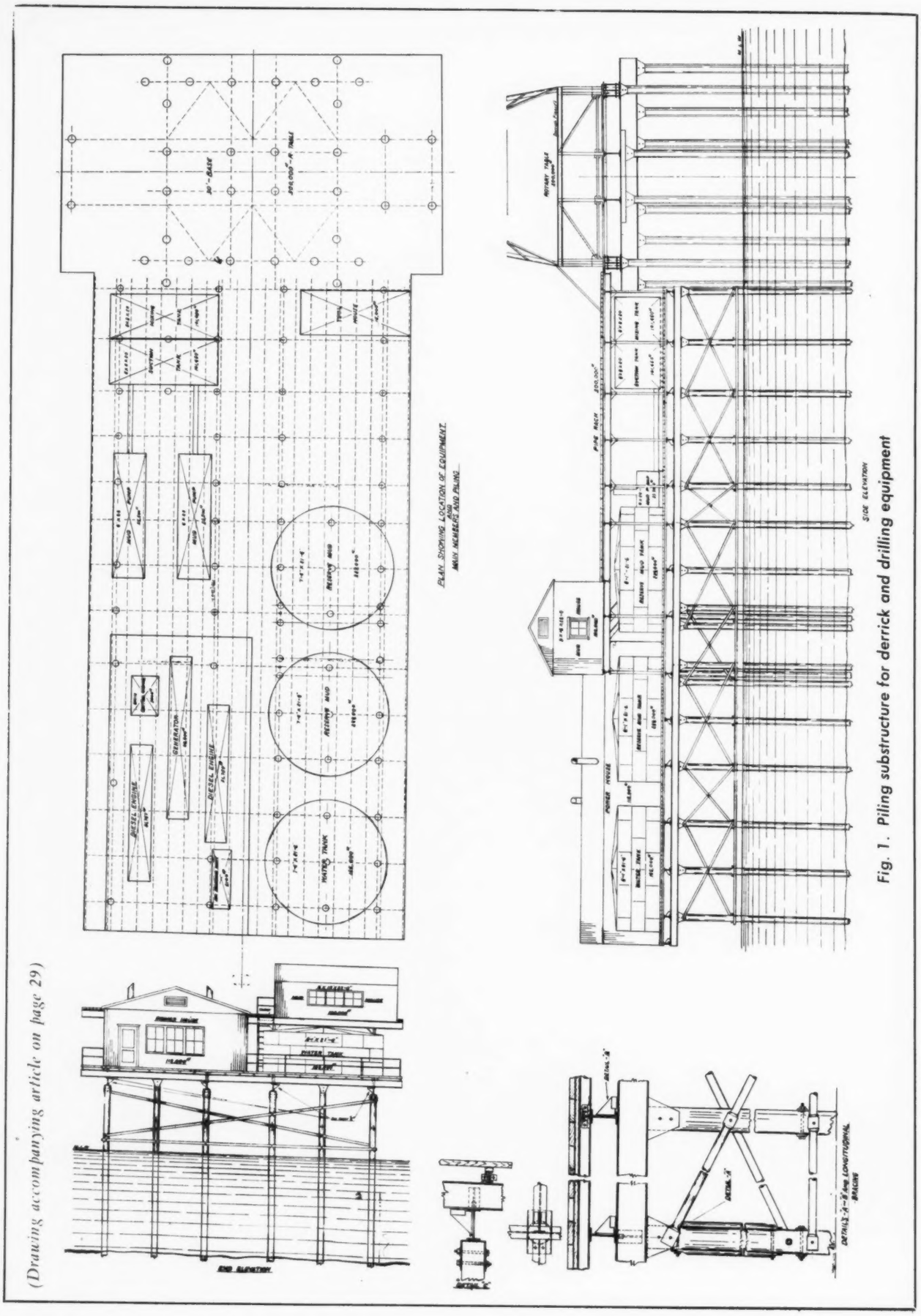

Fig. 1. Piling substructure for derrick and drilling equipment

(Drawing accompanying article on page 29)

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Geodynamic Prospecting for Oil or Gas

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☆ Despite certain limitations, new method holds promise of being a useful reconnaissance tool

by Sylvain J. Pirson

Petroleum Engineer, Geologist, and Geophysicist, State College, Pennsylvania

THE dynamic character of oil and gas fields has long been recognized by geologists. The existence of a commercial accumulation of petroleum and/or natural gas is dependent upon certain requirements: first, there must be a source bed from which the hydrocarbons are derived; second, there must be a trap in the form of a porous geologic structure into which the hydrocarbons move; and third, there must be an impervious cover that prevents the excessive escape or dissipation of the hydrocarbons into the atmosphere.

That there is no perfectly impermeable cover above oil and gas accumulations is an axiom of geology. If the cover was impermeable, it is probable that many petroleum regions would be unknown at this date, because the existence of surface oil and gas in the form of gas seepages, mud volcanoes, sour dirt, asphalt beds, etc.,[1] led the early prospector to the discovery of the major petroleum districts of the world except possibly for the West Texas fields.

Further data that militate in favor of the dynamic character of oil and gas accumulations are the strong geological evidences of the recurrence of successive "crops" of oil and gas over geological time.[2,3]

The prospecting process here under review purports to measure the surface dynamism of hydrocarbons in the subsoil by determining, at the surface of the ground, the rate of gas leakage from subterraneous accumulations as well as from source beds yet in the process of forming oil and gas.

The method is predicated upon the fact that no rock, even though saturated with water, is completely impermeable to gas under pressure. Contrary to some printed statements, it is also known that most sedimentary formations, even below the water table, are not fully saturated with water.

[1] "Direct Indications of the Occurrence of Oil and Gas," by E. De Golyer, *Elements of the Petroleum Industry*, pp. 21-25, A.I.M.E., New York, 1940.

[2] "The Stratigraphical Distribution of Petroleum," by W. A. J. M. Van Waterschoot Van der Gracht, *The Science of Petroleum*, Vol. 1, pp. 58-62, Oxford University Press, 1938.

[3] "Essentials for Oil Pools," by K. C. Heald, *Elements of the Petroleum Industry*, pp. 26-67, A.I.M.E., New York, 1940.

SYLVAIN J. PIRSON

was born in Belgium, 1905—Attended University of Louvain, 1924-29, graduating as mining civil engineer—Granted C.R.B. Educational Fellowship for studies in the United States—Attended University of Pittsburgh, 1929-30, graduating with M.Sc. degree in petroleum geology—Attended the Colorado School of Mines, 1930-31, graduating with D.Sc. degree in geophysics—Further graduate studies in electrical engineering were taken at the University of Louvain and at Technische Hochschule in Hannover, Germany—Instructor in geophysics at the Colorado School of Mines, 1933-34—Geophysicist with Seismograph Service Corporation, Tulsa, Oklahoma, 1934-36—Geophysicist with Gulf Research and Development Company, Pittsburgh, Pennsylvania, 1936—Associate professor of petroleum and natural gas engineering at The Pennsylvania State College, State College, Pennsylvania, 1936, to date—Also is a consultant in geochemical prospecting.

Many horizons are almost dry and very few, if any, are fully water saturated.

Theoretical Considerations

The process of gas leakage toward the surface of the ground finds an explanation in the kinetic theory of gases. In a dry or partly water-saturated horizon, the physical principles involved are those of permeation, diffusion, and effusion. Permeation of a gas through a porous medium is represented by Darcy's Law expressed in differential form by:

$$\frac{dm}{dt} = -\frac{k\gamma}{\mu}\frac{dp}{dr} \quad . \quad . \quad . \quad . \quad (1)$$

in which:

$\frac{dm}{dt}$ = the mass rate of flow of gas

k = the permeability of the medium

γ = the density of the gas

μ = the viscosity of the gas

$-\frac{dp}{dr}$ = the pressure gradient in the direction of flow.

Permeation takes place primarily in porous rocks where the average capillary size is large compared with the mean free path of the gas molecules. A state of viscous flow in the channels occurs under such conditions. If the mean free path of gas is of the same order of magnitude as the capillary openings then it is said that the flow of gas takes place by diffusion, a phenomenon represented by Fick's Law expressed in differential form, on a pressure basis, by:

$$\frac{dm}{dt} = -\alpha\frac{dp}{dr} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which $-\frac{dm}{dt}$ and $-\frac{dp}{dr}$ have the same significance as in equation (1) and in which α is the diffusion coefficient, on a pressure basis, which depends on the medium as well as the physical characteristics of the gas. A comparison of equations (1) and (2) reveals that they are identical if one assumes $\alpha = \frac{k\gamma}{\mu}$. Any conclusion derived, therefore, from the integration of one of the above equations will apply as well to the other phenomenon.

In a fully saturated horizon, the leakage of gas may be explained by effusion or by a process involving solution in the water at the base of the horizon, diffusion of the gas through the water, and liberation of the gas by virtue of Raoult's Law at the top of the water horizon. Again it is assumed that the presence of fully saturated water horizons will not affect materially the leakage distribution unless the water movement is much faster than the gas diffusion through water horizons.

According to the theory, already verified by a number of field measurements, the maximum rate of leakage

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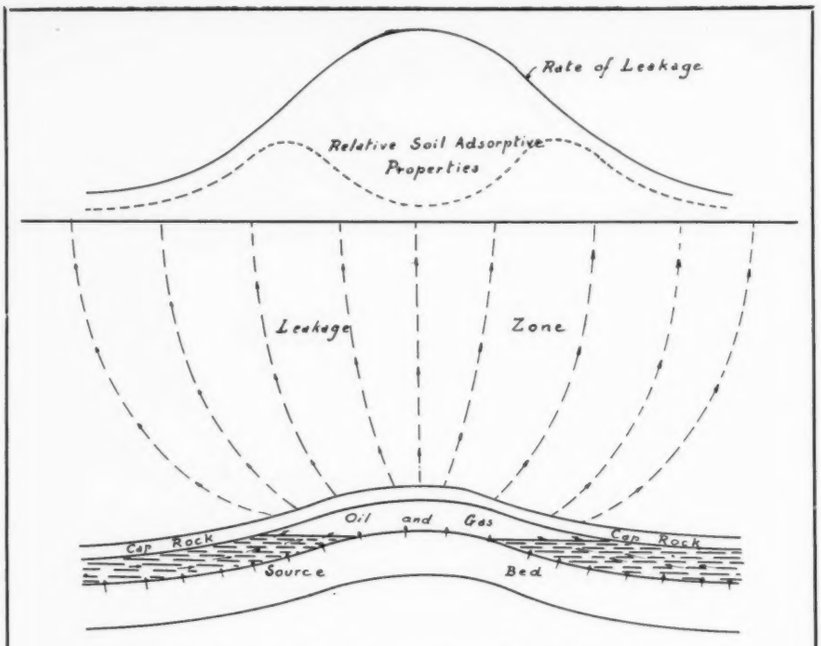

Fig. 1. Theoretical leakage paths and distribution curve

occurs above the accumulation and not a ringlike fashion around it with the reservation that if gravity segregation exists in the reservoir and if one deals with a salt dome free of cap-rock accumulation, then an aureole of high leakage values will be obtained. This must not be construed as a denial of the existence of the so-called "halo" of soil analysis prospecting methods. The writer has observed such a halo in known oil and gas fields when experimenting with soil-analysis and he has found evidences that it is due to changed conditions of the soil by vertical migration of oil-field waters. The ions of oil-field waters become adsorbed by clay particles and change the adsorptive and catalytic properties of clay for gases, generally increasing the degree of retentivity of clays and soils. Although such modified soils, necessarily distributed in a halo fashion around the oil fields are subjected to a gas leakage of less intensity (Fig. 1), they retain more gas than soils located immediately above the oil and gas accumulation, which are subjected to a more intense leakage.

Instead of being contradictory, the methods of prospecting by soil analysis and by rate of leakage measurements are corroborating each other.

The economic advantage of a single series of high values as the required indication of the discovery of a pool in geodynamic prospecting is apparent immediately. When observed in profile it is not necessary to seek a new region of high values in order to establish the necessary evidence of an anomaly as is the case for a possible soil halo. When two highs are observed in soil analysis, there are three possibilities, either the closed halo is outside or inside the two highs. Therefore, transversal profiles must be laid out and analyzed. The advantages of economy and rapidity for geodynamic surveying may be readily seen by the removal of all possible ambiguity. It is estimated that the required number of stations necessary to discover a field by geodynamic prospecting is five times less than by soil analysis.

Although successful measurements have only been conducted for some six months, field tests in Pennsylvania, Mississippi, Kansas, and Arizona have already demonstrated the general practicability of the method.

Measurements

The most economical field procedure in geodynamic prospecting consists in beginning with a detailed profile of stations not more than 500 to 1000 ft. apart. The first profile should be taken at right angles to the expected geological trend in the area under investigation. If anomalous high leakages are observed, short parallel profiles should be taken on both sides of the original profile and about 1500 ft. from it, in the vicinity of the observed anomaly. If the anomaly is corroborated by these short profiles, further parallel short profiles should be tested until no more anomalous readings are obtained. Each individual profile should always extend to a sufficient number of locations at both ends where anomalous readings are not obtained. By such a method, the anomaly will be completely outlined and at the smallest cost.

According to a preferred method of conducting the geodynamic method of prospecting, shallow bore holes, 2 to 3 ft. in depth, and 1½ to 2 in. in diameter are drilled into the surface soil by means of a crowbar. The walls of the hole may be brought to a constant diameter by means of a hand auger; this will also loosen the side wall and permit a free escape of the leaking gas. There is no advantage to drilling deeper holes for gas leakage measurement. The leakage observed at 2 to 3 ft. of depth should be the same 10 or 15 ft. deeper because the leakage in the soil follows lines of flow perpendicular to the surface of the ground. The shallowness of the holes with which the geodynamic process can be carried out is of considerable advantage as the drilling of a 10- to 15-ft. hole is often a difficult and costly matter when practicing other geochemical prospecting methods.

Stations where the field tests are made should be at least 50 ft. from a road, be free from contamination by spilled oils or gasoline, leaky gas from pipelines, etc.

One limitation to the method is that the stations should not be located in ground saturated with free water; however, a fairly high degree of humidity in the soil is not a deterrent.

At each station two or three shallow test bore holes are drilled, but as many as ten may be needed if the rate of leakage to be measured is small.

Into each bore hole is introduced a piezometer, the purpose of which is to retain selectively the gases diffusing into the test hole. Essentially, the piezometer measures the partial pressure rise of a given gas over a period of time. The period of measurement normally is only 24 hours but as much as two to ten days may be required in areas of low leakage. After the required period of time has elapsed, the piezometers are withdrawn from their field locations, sealed, and sent to the laboratory for final checking and measurement. Fig. 2 represents, by means of a diagram, the field procedure used in testing a property for gas leakage.

Assuming that a property of 160 acres is to be tested, a first test line composed of 12 stations 500 ft. apart would be laid out in a direction at right angles to the probable geologic trend in the area. If high values are obtained at stations 4, 5, and 6, shorter profiles (test line 2) would be laid out on each side, 1500 ft. from the first line test and the process repeated until the shorter parallel profiles indicate the presence of low leakage only. In this manner, the high leakage anomaly will be completely defined.

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The results of the measurements may be expressed by means of various physical units but essentially they can all be reduced to a rate of flow of a specified gas by unit area per unit time. At present the measurements employed by the writer are in cu. mm. of ethane at standard conditions of temperature and pressure per sq. ft. per day. The highest readings so far observed in a petroliferous province are of the order of 30 cu. mm. of C_2H_6 per sq. ft. per 24 hr., which is equal approximately to 10,000 cu. ft. of ethane per sq. mi. per year. These measurements were obtained above Devonian oil and gas fields in Pennsylvania 200,000,000 years old. Therefore, if the rate of leakage has been constantly equal to the cited figure, the Devonian fields have leaked a total of two trillion cu. ft. of gas per square mile since the time of their formation. Unless replenishment during geologic time is assumed, these oil and gas fields, therefore, would be depleted at this time. This is well in accordance with the views of Van der Gracht and Heald[2,3] and oil and gas structures must be conceived as reservoirs constantly fed by source beds and constantly depleted by leakage.

According to these views, an oil and gas accumulation would be due to the introduction of a barrier, the cap rock, in the path of the leaking oil and gas from the source bed. This hypothesis is schematically represented by Fig. 1, showing the paths by which the oil and gas is concentrated in the reservoir and by which the lighter hydrocarbon gases leak out from the structure toward the surface of the earth.

Example of Field Results

Fig. 3 represents the results of a blind survey made in Kansas north of Macksville, Stafford County, over a recently discovered pool. The test was experimental in nature and designed to determine the degree of reliability of geodynamic prospecting.

At the time of the survey only the discovery well was drilled. Geologic information on the structure and the location of the stations with respect to the known information were withheld from the writer until the laboratory tests were completed. About one-third of the tests were made on top of the structure and two-thirds outside the structure.

The results of gas leakage measurements as related to the known geologic information are given in Fig. 3. From seismograph information it is expected that the axis of the pool trends NW-SE and that about 40 ft. of closure is present. The discovery well was drilled before the field tests were completed whereas the dry hole was drilled-in before the laboratory tests were completed. It can be noticed that the geodynamic tests show a gradual increase of the rate of leakage when approaching the axis of the structure. It is also worth noting that both the geologic and geodynamic information were unable to condemn the dry hole where the sand was found to be 20 ft. lower than in the producer. This failure might be due to the erratic character of the producing horizon.

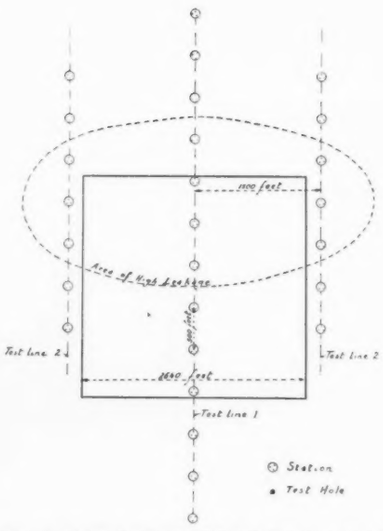
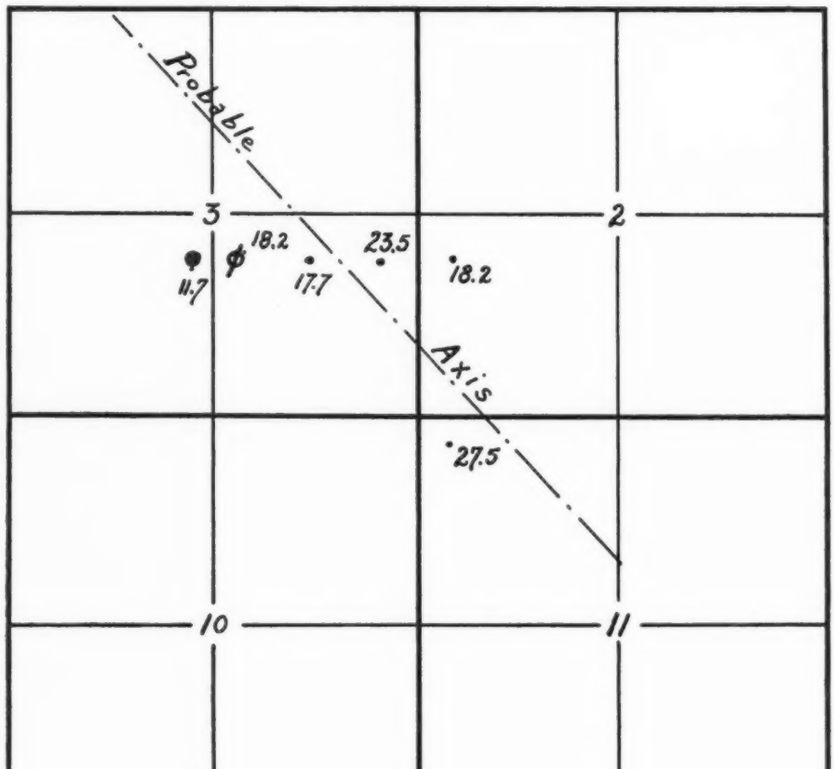


Fig. 2. Distribution of field stations and test holes in rate of leakage measurement prospecting

Conclusions

It appears to date that geodynamic prospecting holds great promise of being a fast reconnaissance tool particularly for stratigraphic pools. A certain number of limitations now exist such as the inability to work in water-saturated soils. This may, however, be remedied if a more expensive field procedure is used. The method further depends on the application of the theory of potential functions to the interpretation of the results and, as such, has a certain number of limitations, inherent to such methods particularly in defining the exact producing limits of an accumulation. It has, however, the advantage of being a direct method for finding oil and gas pools under pressure and to indicate their presence by a single set of high readings made immediately above the accumulation. Depth predetermination and separation of individual horizons is also possible within reasonable limits.

Fig. 3. Results of geodynamic prospecting in Stafford County, Kansas
(Surface leakage in cu. mm./cu. ft./day)



Oil and oranges, side by side. International U-6 Power Unit operating a well in the East Coyote field near Placentia, Calif. The U-6 develops 41 h.p. at 1,500 r.p.m.

Typical power unit installation in the West Texas-New Mexico Permian Basin near Odessa, Texas. International U-4 shown. Develops 31.5 h.p. at 1,800 r.p.m.

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Refinery Piping—Design of Stock Lines From Tower

☆ Design of compressed air lines also discussed

by R. G. Lovell

Development Engineer, Hancock Oil Company of California

IN CONVEYING overhead stocks from the fractionating tower to treating equipment, or to condensers, one or more of the lines will handle the stock in vapor phase. This, however, will not complicate the study because extreme conditions of temperature and pressure do not exist.

Removal of the side cuts and bottoms, which are in liquid phase, requires only the intelligent application of the rules brought out in previous articles by the writer. Knowledge of these rules does not necessarily imply that proper application of them will follow. Profitable use of the rules frequently amounts to direct reversal of their aim. Proof of the reversal will be shown later in considering the lines carrying intermediates and bottoms away from the distillation equipment.

Gasoline Vapor Line

The gasoline vapor line may have as its terminal either a clay tower or a condenser, depending upon the type of treatment in use. If vapor phase clay treating is practiced there will be an advantage in maintaining the temperature of the vapors as they leave the tower. This, of course, indicates insulation of the line. On the other hand, if the vapor line goes directly to a condenser, not only is heat insulation unnecessary, but there is an obvious disadvantage in its use, as it is desired to remove heat from the contents of the line. Further, a dull, dark-colored finish on the pipe will add to its ability to dissipate heat.

Size of Line

Rules applying to flow of liquids in pipe will not apply here but a simple and sufficiently accurate equation is as follows:

$$D = \sqrt{\frac{g \times 0.05}{0.7854}}$$

where:

g = total distillate in gal. per hr.

D = diameter of vapor line, in.

The operator should not overlook the amounts of reflux and steam used and be sure to include these volumes in the figure for the total volume to be piped. Using this formula, with adequate allowances for reflux and steam, it is found that a 16-in. line will be required. The values used to arrive at this figure are:

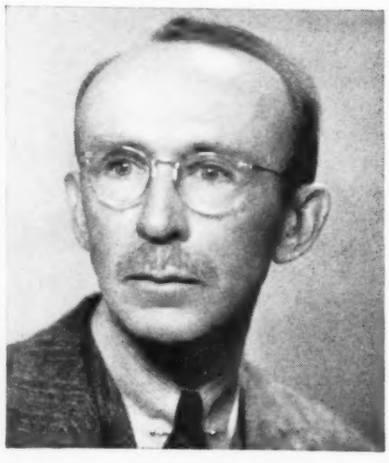
Percentage of vapor overhead to crude charge = 20

Reflux ratio = 2½

Steam (water) = 180 gal. per hr.

Total distillate using these values would be 3680 gal. per hr. and the value of D becomes approximately 15.5 in.

There is no valid reason for the use of standard weight pipe for this line. Its wall thickness can well be determined by that which is presently considered the minimum for proper welding (14 gauge.) Use of lightweight pipe not only lowers the cost of the line, but simplifies the job of supporting it. Flanges should be of mild steel; all supports of the line should be made from the flanges rather than from clamps on the pipe.



R. G. LOVELL

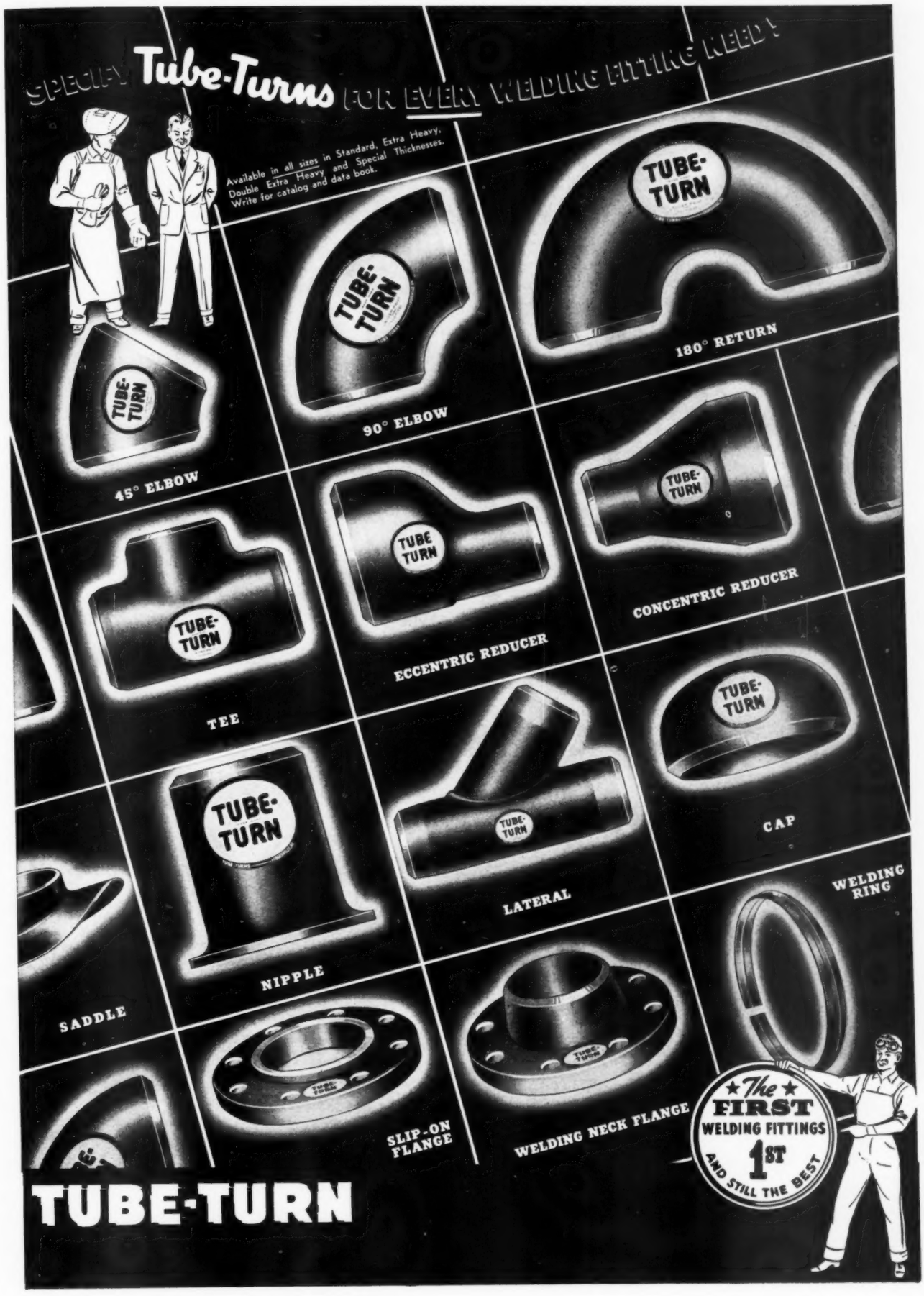
received his academic training in New York and served several of the larger mining and milling companies of New Mexico, Arizona, and the Republic of Mexico as power engineer and master mechanic from 1908 to 1917, then saw military service in the engineering corps until 1919—Returning from the war he became affiliated with the oil refining industry, first with Standard Oil Company of California as refinery construction engineer and later with a foreign company—Later he was made assistant to the chief engineer of Pan American Petroleum and Transport Company for the construction of their California processing properties—He has been with The Hancock Oil Company of California since that time—Lovell is the senior instructor of the class in practical petroleum refining, which he organized several years ago, for the Trade Extension Division of the Long Beach High Schools—The class is attended by employees of the many companies operating in the southern California fields.

From Condenser to Run-Down Tank

There is now a mixture of liquid gasoline and water to be handled, which should be separated and the water discarded as quickly as is practicable. Three reasons are manifest for accomplishing this separation before reaching the run-down tank: first, water in the tank is not "pay load"; second, more active corrosion on tank bottom occurs when water is present, and third, evaporation losses are greater from a gasoline-water mixture.

Many devices have been developed to make this separation automatic but not all have proved successful. Included are those that depend upon a weighted float and compound leverage for operation. The operator will often elect to make periodic manual water withdrawals from the rundown tank because of the ever-existing possibility of gasoline running to sewer for a considerable time before discovery, through failure of the float mechanism to function.

Another type that does not depend in any way upon floats or mechanical equipment, is shown in accompanying sketches, Figs. 1 and 2. The only objection that the writer has ever heard to the use of this type is that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wide variation in the specific gravity of the gasoline would require a change in point of water drawoff. We shall see directly if this objection is justified.

Fig. 1 shows how the desired end can be accomplished in the conventional way when the separator is not intended to function as a reflux accumulator.

Fig. 2 is shown with a baffle, or separator, which provides a reservoir for reflux. Great care must be exercised in the manufacture of the type shown in Fig. 2, for the results of even a slight leak in the joint between the baffle and the body may be serious. In both instances provision must be made to transfer any vapor pressure from the body back to the vapor space of the rundown tank where the vapor can be taken care of by the regular tank vapor relief devices.

The very simplicity of this type of separator has caused it to be subjected to close scrutiny and some amount of skepticism. It has been difficult for many to realize that the point of water drawoff can be above the water level in the body. Certainly the most satisfactory way of dispelling this skepticism is to reason out the matter by designing a unit to handle the duty for a typical case using the same values that have been set-up heretofore.

The Volume Duty

The total amount of distillate, including steam and reflux, was developed in the last calculation as 3680 gal. per hr. of which 180 gal. is water. The job, then, is to select a vessel that will be ample in area to permit complete separation of the water, and of such height that the gasoline can flow by gravity to the rundown tank, and the water be discharged to sewer by an open jet so that it can be checked readily. Observe in the accompanying sketches that the gasoline level is controlled entirely by the height of the weir, which must, of course, be above the highest point in the rundown line. This does not necessarily involve an unduly tall separator as there is usually plenty of vertical distance in which to work, and the condensers can be placed high enough to provide liberal clearance.

Assume a diameter of 5 ft.-10 in. and a distance of 4 ft. from point of entry of the gasoline-water mixture to the normal gasoline level. The contained separation area will be 600 gal. If the mixture to be separated is entering at a rate of 3680 gal. per hour, or 60 gal. per minute, any unit portion of the liquid will require 10 min. to reach the weir and pass out. This is ample time to insure that no water will remain entrained with the gasoline. If the vapor space of the separator is connected with the vapor space of the rundown tank, as has been recommended, no condition of vapor pressure can alter the time allowed for the separation to take place. And, no matter what method of removing the gasoline from the separator is used, the time element is not changed so long as there is a break between the weir and the outgoing stream.

Having found that 4 ft. is ample travel time in which to remove completely the water from the gasoline, we next need to know how much travel time to allow for the water to rid itself of the gasoline before entering the water discharge line. The water is only 5 percent of the total volume but the penalty of carryover is loss of gasoline. Prudence, therefore, indicates still slower travel. Three ft. of water depth should be entirely satisfactory and safe. The total height, then, from the bottom of the body to the normal gasoline level will be 7 ft. A vapor space of 3 ft. should insure against any rapid rise in vapor pressure.

Locations of Water Drawoffs

The height above the bottom of the body at which the water drawoffs are taken is not determined by the relative volumes of the two liquids. These points are established by the dimensions just used, taken together with the specific gravity of the gasoline. As a basis for the first calcuation we will assume an A.P.I. gravity of 57° (0.75 actual specific gravity) for the gasoline. The pressure exerted by a 4-ft.

Gasoline-Water Separator

Fig. 1

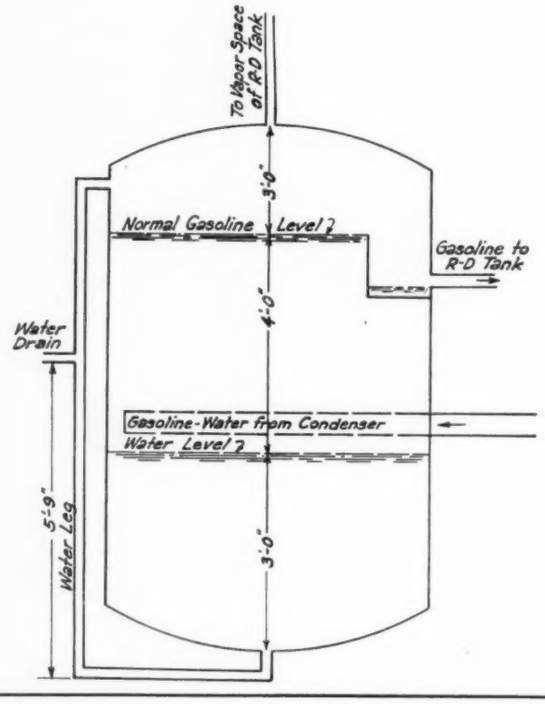
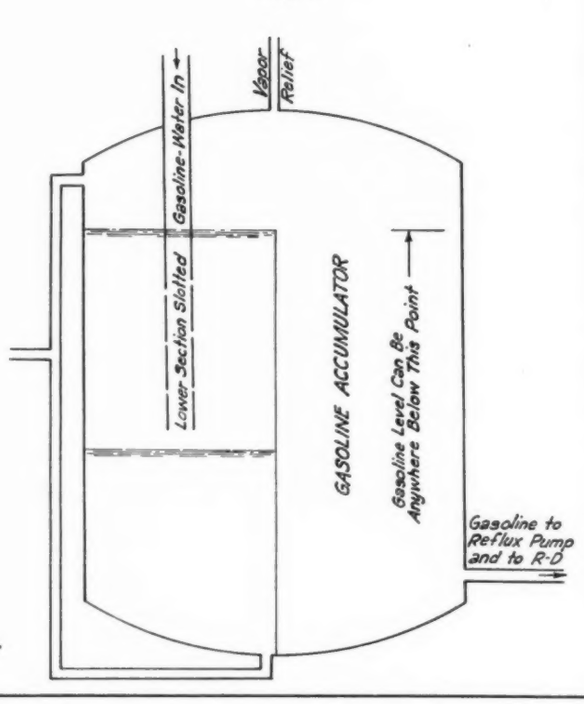


Fig. 2


Vapor Relief
Gasoline-Water In
Lower Section Slotted
GASOLINE ACCUMULATOR
Gasoline Level Can Be Anywhere Below This Point
Gasoline to Reflux Pump and to R-D

column will be 4 × 0.434 (pressure of a column of water one ft. in height) × 0.75 = 1.3 lb. per sq. in Three ft. of water will exert an additional pressure of 3 × 0.434 = 1.2 lb. per sq. in. The total pressure inside the separator that forces the water up in the leg is 2.5 lb. per sq. in., which will support a column of water

$$\frac{25}{0.434}, \text{ or } 5.76 \text{ ft.},$$

which is 5 ft. 9 in. *If a water outlet is located at this distance above the lowest point in the separator and the gasoline is approximately 57° A.P.I., the unit will function without attention and no one need go near it.*

Refinery operators know that the gravity of the gasoline stream can change suddenly for several reasons. Let's see how the proper functioning of the separator is going to be affected by such changes. Suppose, for instance, that the crude oil charge pump should speed-up without the heater fires being increased, or that the fires become diminished without change in the charging rate, or that the distillation steam supply is reduced. The effect would be the same in any case. The gasoline cut would be less deep, with a consequent increase in its A.P.I. gravity or lowered specific gravity. The water-gasoline ratio would also be affected by change either in fire or charging rate, but not to any considerable degree by a reduction in amount of steam. In the latter case, as the steam was reduced so would be the amount of vapor distilled; therefore, the ratio would not be materially changed.

In the event of either of the first two contingencies, the total amount of liquid coming to the separator would be considerably reduced, but this would have no effect upon the normal gasoline level. The gasoline would simply pass over the weir at the same reduced rate and, as the rate of water remains the same, the volume of water would tend to increase. Recollect, then, that the height of water discharge was determined from a definite relationship between the specific gravity of the gasoline (0.75) and water (unity or 1). Inasmuch as the gasoline now has lower specific gravity, say 0.74 (60° A.P.I.), the water will occupy some of the vertical distance allotted to the gasoline under the previous specification of 57° A.P.I. This increased height of water will be just enough to overcome the lesser weight of the gasoline and bring about the same pressure (lb. per sq. in.), at the base of the water leg as existed before.

This contingency, as well as the idea that a separator designed as indicated, would be unsuitable for use with gasolines of different specific gravities, has actually restrained many operators from using the device. To calculate accurately the changes in relative depths is relatively simple. If the total pressure, lb. per sq. in., of the two heights of liquids that were considered necessary for complete separation was 2.5, and the respective specific gravities were as 0.75 (57° A.P.I.) is to 1.00, then when we change specific gravity of the gasoline to 0.74 (60° A.P.I.), we vary the height relationship in the same degree. The previous depth of water, 36 in., was related to the specified gasoline depth in the proportion of 3 to 4. The depth of water must increase in proportion to the depth of gasoline in order to maintain the total pressure if the gasoline becomes lighter. The problem is worked simply, therefore, by multiplying the original depth of gasoline, 48 in., by 0.76, which results in 36.48 in. Obviously, the gasoline depth will be 84—36.48 or 47.52 in. This should remove any question concerning the flexibility of this type of separator.

Fig. 3. Gasoline-water separator without floats or levers

Piping Straight-Run Bottoms From Tower

To handle this job of piping only from the angle of getting the stock away from the distillation unit is another practice that we cannot longer afford to continue. The proposition is simple in its fundamentals: a known quantity of stock of known temperature, part of which is desired to be used for cracking plant charge stock at existing temperature, and the rest is to be divested of some part of its heat by surface transfer to incoming crude oil. Desirable temperature and quantity ranges are well understood, as are the relative importance of each of the desired conditions. It remains only to devise a means of accomplishing, not a perfect condition of balance, but one that offers the ultimate in practicability at a cost that is justified by the actual return in dollars and cents. A practical scheme for this purpose was shown in a previous article.[1]

In subsequent articles it is intended to work out the heat transfer problems involved in the scheme. For the present we will confine ourselves to the more immediate phases, those of so arranging the piping that full advantage can be had from the idea.

Greatest flexibility, highest efficiency, and ultimate in control is had, of course, by using two pumps for this service. One to transfer hot bottoms to cracking without loss of heat and the other to force the remainder of the bottoms through the heat exchanger bank and on to storage. The head duties of these services are widely different and, consequently, two pumps of different characteristics can be used to good advantage. In any case, to provide such suction line conditions as will assure that the pump constantly has flooded suction is vitally necessary. This is not usually difficult because of the normal head of several feet of stock in the bottom of the tower. The pump ordinarily can be placed close to the tower base.

Side Cuts From the Tower

Not much need be said about sizes or methods of installing lines for kerosine distillate or gas oil from towers to coolers and thence to rundown tanks. Lightweight, welded lines are much cheaper to install and have a satisfactory life. Mild steel flanges should be used and flanged openings left at intervals.

There is one point to be observed in piping these side cuts from tower to coolers. Provisions must be made for keeping the cooler filled with the stock

[1] "Refinery Piping . . . Design of Line from Charging Pumps to Flash Towers," by R. G. Lovell, *The Petroleum Engineer*, May, 1941.

at all times. This is usually done by leaving a small opening for a vent line as the line leaves the cooler and turns downward. If, however, the coolers are situated below the level of the run-down tanks, this precaution obviously is unnecessary.

It will often be found useful to provide a means for diverting some or all of the gas oil, before it reaches the cooler, to the cracking plant charge. This is a simple matter of leaving a flanged opening and running a connection to the manifold at the primary heat exchangers.

Compressed Air Piping

Compressed air has limited application in an oil refinery. It is generally used for power to operate motor control valves for liquid level and for tube-cleaning turbines. The motor valves consume but a very small amount at low pressure, usually about 15 lb. The important requirements are that it be free from dirt, scale, or water, and that its supply be dependable.

Tube-cleaning devices consume relatively large amounts of high-pressure air but their use is often periodic. It is standard practice in such cases to provide two entirely separate systems. One supplied by duplicate small compressors, for insurance of continuity of service, the other by larger machines, either steam-engine- or electric-motor-driven. Choice of the type of drive is usually determined by power costs. Single-stage, air-cooled units are entirely practical for the motor valve service. Single-stage compression obviates much of the trouble from rust caused by water in the line.

To use two or more stages in which to bring air to a desired high pressure is made necessary by the difficulty of obtaining satisfactory lubrication at the high temperatures caused by compression and by the extremely close piston-to-cylinder head clearance involved in single stage, high compression. For example, to compress air at sea level to 100 lb. per sq. in requires that the clearance volume, including valve recesses, at end of compression stroke be only one-seventh of the cylinder volume at the other end of the stroke. As the valve passages must be included in the clearance volume, there is little actual end clearance and, consequently, rod elongation, loose piston, or bearing wear can cause striking.

In multi-stage compression a part of the heat of compression is removed in intercoolers. When this air is again expanded to atmospheric pressure in the device using it for power, its temperature will be much lower than the outside air because the heat of compression has been removed. This is frequently the cause of trouble from ice formation in exhaust ports. The accompanying moisture also makes lubrication unsatisfactory and reduces the latent power of the compressed air. If compressed air produced by multi-stage compression is reheated the gain in power will be found to be in excess of 15 percent.

A compressed air flow chart is shown that will be found useful in determining proper sizes of compressed air lines. In most cases, when tube cleaners are the main duty, a chamber, or an enlarged diameter of a section of line placed adjacent to the point of use, will make practicable a somewhat reduced line size. This should be so connected that it may also serve as a trap for removing moisture.

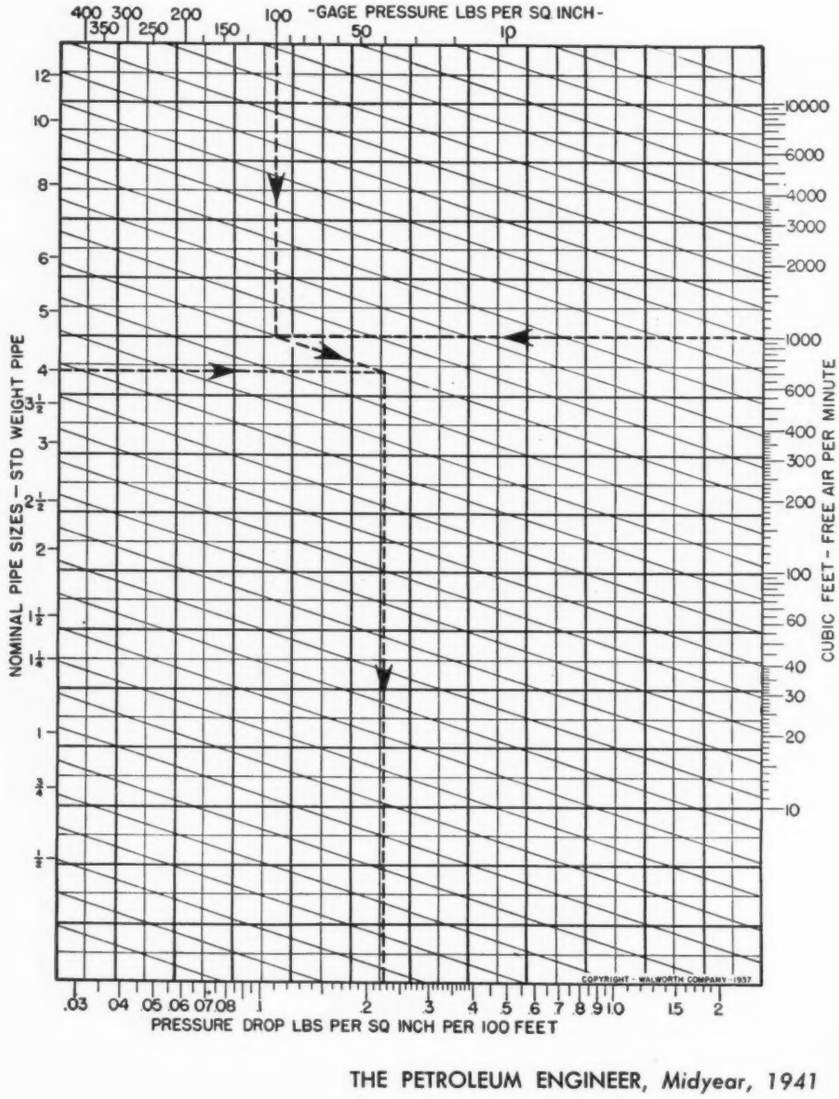
Compressed Air Flow Chart

Problems: One thousand cu. ft. of free air per min. is to be transmitted at 100 lb. per sq. in. pressure through a standard weight 4-in. pipe. What will be the pressure drop due to friction?

Solution: Enter the chart at the top, at the point representing 100 lb. per sq. in. pressure, and proceed vertically downward to the intersection with a horizontal line representing 1000 cu. ft. per min., then parallel to the diagonal guide lines to the right (or left) to the intersection with a horizontal line representing a 4-in. pipe, then vertically downward to the pressure loss scale at the bottom of the chart, where it is observed that the pressure loss would be 0.225 lb. per sq. in. per 1000 ft. of pipe.

Unknown Quantities: Four quantities are involved in the use of the chart, viz., air pressure, rate of flow, pipe size, and pressure loss. The chart may be used to determine any one of the foregoing data, provided the remaining three are known.

Fig. 4. Compressed air flow chart


400 300 200 100 -GAGE PRESSURE LBS PER SQ INCH-
350 250 150 50 10
NOMINAL PIPE SIZES – STD WEIGHT PIPE
12 10 8 6 5 4 3½ 3 2½ 2 1½ 1¼ 1 ¾ ½
CUBIC FEET – FREE AIR PER MINUTE
10000 6000 4000 3000 2000 1000 600 400 300 200 100 60 40 30 20 10
.03 04 05 06 07 08 1 2 3 4 5 6 7 8 9 10 15 2
PRESSURE DROP LBS PER SQ INCH PER 100 FEET
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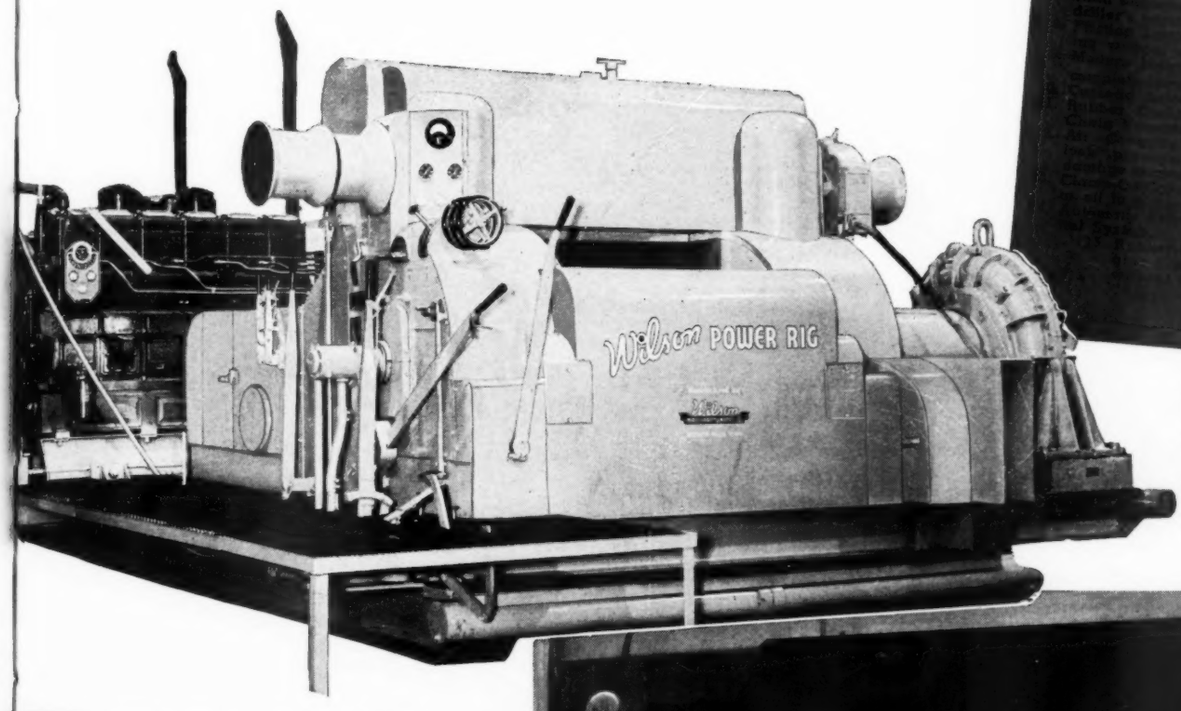

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Twin wells on separate pier foundations were directionally drilled

PETROLEUM ENGINEER Exclusive Feature

by

Wallace A. Sawdon

Pacific Coast and Foreign Editor

Factors Involved in Pumping Directionally Drilled Wells

☆ Lifting cost and subsurface equipment wear reduced by careful control of direction in slant-hole wells

ADDITIONAL wear on subsurface equipment during pumping due to the deviated course of a slant-drilled hole must obviously be given due consideration by production men; but the time to begin considering this maintenance factor is when the well is being drilled. With the present advanced technique of controlled directional drilling this wear is reduced to a minimum and when due care is exercised in changing the course of the bore to make the transition a smooth curve, the wear on tubing and rods will frequently be less than in a hole intended to be vertical in which rectifying changes to straighten the hole are made too sharply.

Probably more slant holes have been drilled in California than in any other oil-producing territory in the world. In some cases the topography has made the use of directionally drilled wells absolutely obligatory; in others, the locations on the sand have been such that considerable time and money have been saved by drilling slant holes from other surface locations. The horizontal distance from the well mouth to the predetermined location in the producing zone has ranged from a comparatively few feet with small angles of inclination (as necessary for sidetracking or redrilling) to from 3000 to 3500 ft.

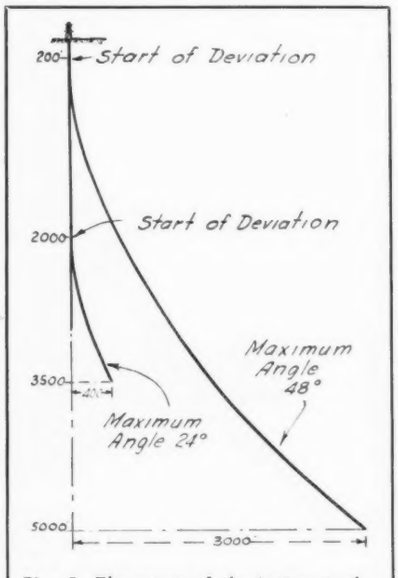
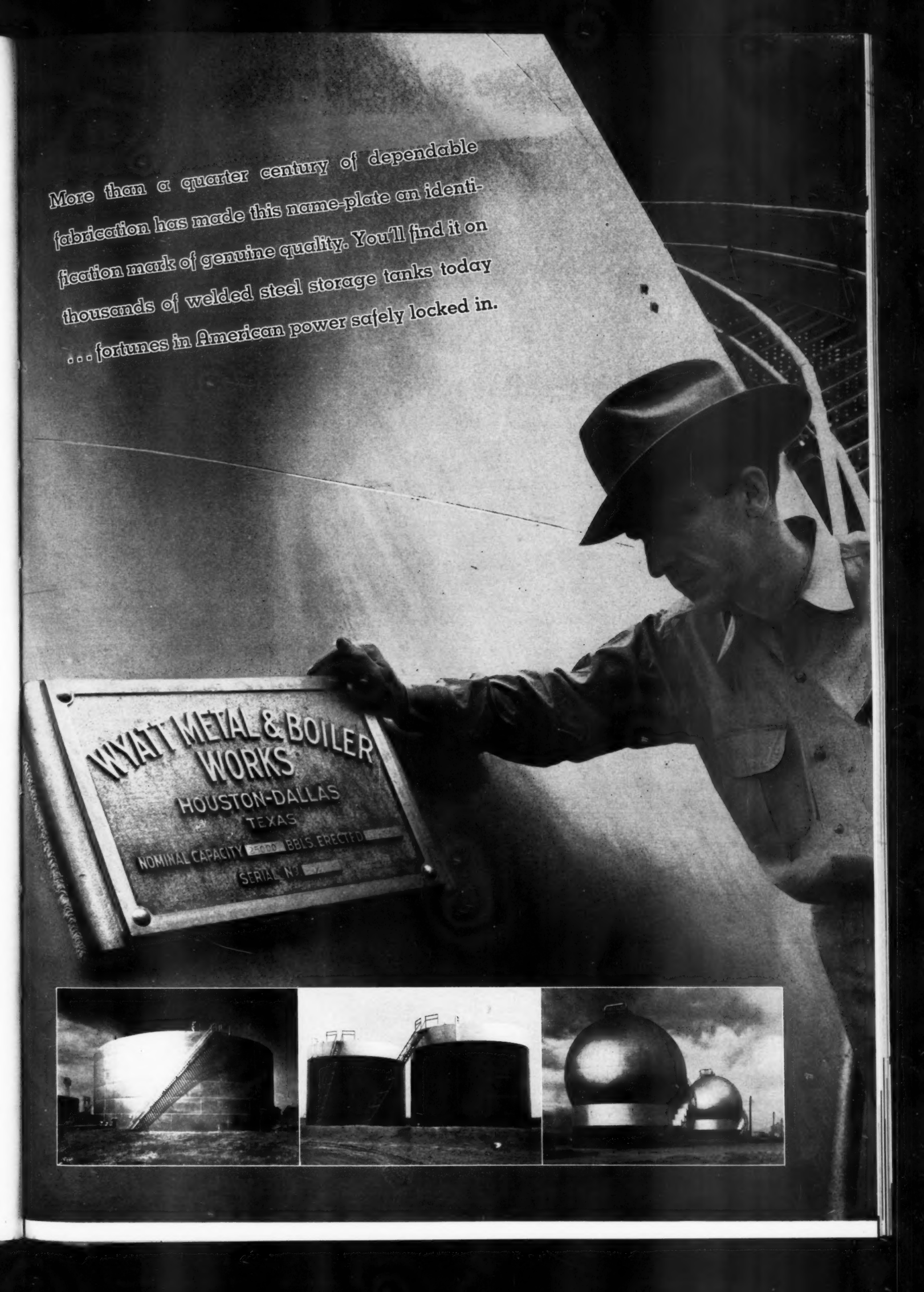


Fig. 1. The start of deviation is determined by amount of horizontal drift desired and depth to producing formation

with angles of 60 deg. or more as is the case with some of the wells drilled below the ocean at Huntington Beach. No matter how small or great the inclination is, however, the care with which the changes of inclination and direction are made will be reflected in future pumping costs.

Details of directional drilling methods will not be discussed but there are certain general features that must be considered if wear on rods and tubing is to be reduced to a minimum. Only one general change should be made in the course of the hole and this should be done with as gradual a build-up to the maximum angle as possible. That is, beginning from the vertical the course of the well should be planned so that the curve formed by the bore should not have to be brought back to a smaller degree of inclination before the bottom is reached. In some instances wells have been brought back to vertical before reaching the sand but this gives an extra bend over which the rods must travel. The depth at which deviation should begin is determined by the amount of horizontal drift desired and the depth to the producing formation. As indicated in Fig. 1, the devia-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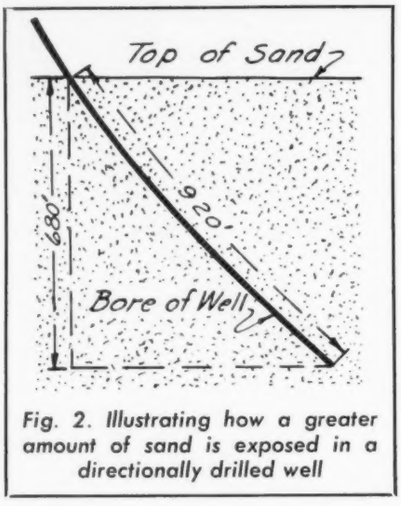

Fig. 2. Illustrating how a greater amount of sand is exposed in a directionally drilled well

tion in a 5000-ft. hole that is to drift 3000 ft. should be started much higher than a 3500-ft. well that is to bottom 400 ft. distant. In an 8000-ft. well that is to bottom 300 ft. distant from the vertical the deviation would probably not begin above 6000 ft. under average conditions. No rule, however, for the point at which to begin deviation can be established for certain designated depths and horizontal drifts as the formations and other subsurface conditions must be taken into consideration. The deviation is seldom begun, however, until after the surface string has been set, although one company at Huntington Beach begins at approximately 200 ft. when 5000-ft. (measured, not vertical depth) wells are to extend approximately 3000 ft. horizontally from the surface location.

Direction Control

The control of direction is usually much more difficult than control of vertical angle, but sharp angles must be avoided in rectifying a direction drift. When feasible, the hole should begin on a direct horizontal line toward its objective; unfortunately, this is not always possible but when a change in horizontal direction is necessary, obviously it should be made with as smooth and gradual a curve as conditions permit.

The course of a slant hole is usually platted as the well is being drilled. Every effort should be made to obtain as complete a survey record of the underground course as possible. The survey will help in locating trouble that may arise at a later date and when properly interpreted may aid materially in cutting down lifting costs. In a great many slant-hole wells now on the pump, sucker rod guides are used to protect the rods and tubing against wear. The placing of the guides for this purpose is determined most effectively by utilizing the survey of the well. The pump should not be placed at a point where the change of course is great as the plunger may stick or score.

Increased study is being given to fluid levels, sand conditions, formation characteristics, and other factors before selecting the type and size of equipment for use in any well being put on the pump. Such studies are probably even more important with slant wells than with vertical holes. The height of the pump setting is governed, of course, by production requirements but it will frequently be advantageous to set the pump as high as possible without unduly affecting performance as determined by other factors. The anchor-type tubing catcher is widely used for anchoring the tubing, and gas anchors are employed where advisable.

Under present curtailment requirements there is no effort to get maximum production from any pumping well. From past experience, however, it appears that high speed pumping is detrimental in slant holes. The present speeds being used in deviated wells are as low as 12 s.p.m. but some are being pumped at speeds greater than 20 s.p.m. Strokes range in length from a minimum of 30 in. but the 60-in. stroke is probably more widely used for slant-hole pumping at the present time. At the lower speeds there is an understroke and at higher speeds an overstroke. This is true for all pumping wells, of course, but it is interesting to note that in one well having a high angle of inclination and a considerable horizontal drift a stroke of 64 in. at the surface was compared with the stroke resulting at the pump under high speed pumping and was found to be 80 in.

Wear on Subsurface Equipment

There is undoubtedly greater wear on pumps, rods, and tubing used in a slant hole than in vertical wells. In earlier days at Huntington Beach when many slant wells were drilled somewhat haphazardly with the intention of getting to a distant point on the sand as fast as possible, sufficient consideration was probably not given to sharpness of bends. The wear on rods and tubing in these wells is thus greater than in wells drilled with future production maintenance in mind. It was once thought these wells could not be pumped with rods; yet the troubles have not been as serious as anticipated. Other older slant hole wells, however, were drilled with better direction control. In a well slant-drilled at Elwood ten years ago to a depth of slightly more than 3000 ft. with a drift of approximately 400 ft. the production troubles have been less than in a vertical well near-by. At that time vertical drilling was not up to present standards and more care was probably taken in putting down the slant hole than in drilling the vertical one. Consequently, comparisons of older wells are not reliable.

Of the recent wells directionally drilled with great care there are many that have not yet shown signs of wear on equipment. They probably will eventually show greater wear than recently drilled vertical wells but evidence as to the extent of this excess wear cannot yet be determined. Other somewhat older wells drilled with equal care, however, have disclosed factors that influence wear and indicate what may be expected under various conditions.

Three wells, directionally drilled from a pier, pumping on one location

PETROLEUM ENGINEER EDITION

BAASH-ROSS News

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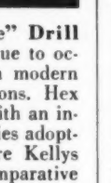
A MONTHLY BULLETIN COVERING NEWS OF EQUIPMENT AND OPERATIONS IN THE PETROLEUM INDUSTRY

BAASH-ROSS REPORTS TO THE OIL INDUSTRY ON LATE DEVELOPMENTS AND OPERATING TRENDS

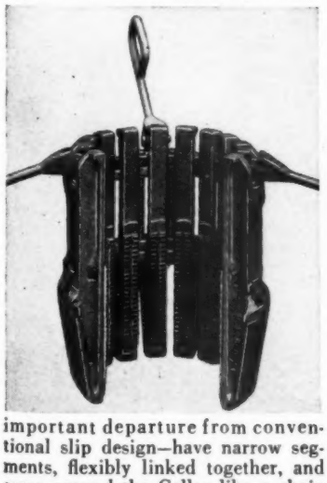
In this Annual Engineering Review Issue of the *Petroleum Engineer* will be found records of recent important accomplishments in the oil industry. In many of these achievements, Baash-Ross equipment has played an important role. In fact, it has always been the Baash-Ross policy, not simply to keep abreast of the industry, but to keep *ahead* of it...pioneering new developments, new engineering advancements, new ways of getting the job done better...faster...*at lower over-all cost.* Herewith are interesting news notes about Baash-Ross equipment and recent developments...

ROTARY DRILLING

Baash-Ross "Trubore" Drill Collars and Kellys continue to occupy the No. 1 position in modern high-speed drilling operations. Hex Kellys hold the spotlight, with an increasing number of companies adopting them to replace square Kellys after making exhaustive comparative field tests. Any company doing drilling work of *any* kind should investigate the many basic advantages of Hex Kellys!

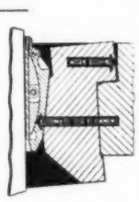


Two revolutionary Baash-Ross *safety* developments of the year—(1) *Drill Collar Slips* and (2) the *Safety Clamp*—have proven extremely popular. The *Drill Collar Slips* are an important departure from conventional slip design—have narrow segments, flexibly linked together, and *wrap* around the Collar like a chain tong. They *always* give the same full grip *regardless of wear or out-of-roundness of Collar.*



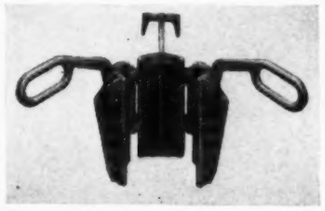
The Safety Clamp, also, is made up of small segments, flexibly linked together. It can be quickly fastened around streamlined drill collars and other flush joint equipment, forming a safety stop that prevents equipment dropping into hole. Should be on every rig!

Baash-Ross Roller Kelly Bushing continues to set new standards of sensitive weight control and frictionless kelly feed. First 2RS Roller Bushing still going like a whirlwind after drilling equivalent of *fifteen* 5000 foot wells without a cent for repairs of any kind. Many companies, after testing, are adopting Roller Bushings as "must" equipment!



Baash-Ross "Self-Aligning" Slips are saving operators many hundreds of dollars in reduced pipe damage and increased crew efficiency. "Self-aligning" principle permits gripping member to automatically align itself with pipe regardless of wear or mis-alignment in master bushing bore.

Baash-Ross Type "CU" Rotary Slips are proving more and more popular among crews. The three segments always maintain perfect alignment vertically, eliminating pipe marking and damage from setting one slip too high or too low. Some operators prefer this type, others the "Self-Aligning" above. Both are top-notch in operating efficiency!

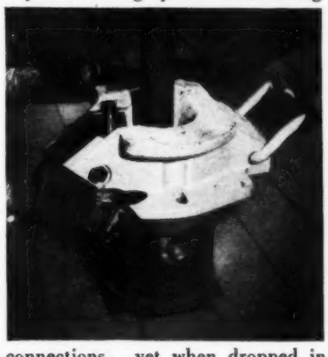


SLIM HOLE DRILLING

One of the newest Baash-Ross developments is a special swivelling Clevis for use with the *Baash-Ross Streamlined Tubing Block* in slim-hole drilling. The Clevis replaces regular bail on Block. Elevator links fasten directly to the Clevis, eliminating need for Hook. The Clevis is spring loaded, free-swivelling (with lock to prevent rotation, when desired) and has other valuable features. By eliminating Hook, it saves valuable space in derrick...a particularly important point on slim-hole rigs!

PRODUCTION

Baash-Ross Open-End Tubing Spider leads modernization parade. Operators like its dove-tailed end-gate feature that can be quickly removed to permit setting-up without breaking connections...yet when dropped in place, rigidly locks entire unit into one piece that will not spread under heaviest loads. Tubing slips have been improved with a new quick-acting lock. Lock snaps shut *automatically* when handles are closed, opens *automatically* when handles are spread. Fast, efficient!



Many new Baash-Ross Streamlined Tubing Blocks go into the fields. On this Block all bolts, nuts, pins, grease fittings, etc., are *completely recessed* into "pockets" in side plates. Not a sharp corner or projection *anywhere* to catch on *anything*—either obstructions in the derrick or clothing of workmen. An important safety advancement. Has other major features, also. (Example, see Slim-Hole Drilling.)

Another important development of the year is the *Baash-Ross Utility Block.* Simple accessory fittings make block into (1) Floor Block, (2) Tubing Block, or (3) Bailing and Coring Block. *Buy* one block, *maintain* one block...but get efficiency of THREE blocks!

Speed of production work in industry is being steadily improved by widespread use of *Baash-Ross Wire Line Wiper* on bailing, swabbing and other wire line work. Wipes line *clean* as it comes out of hole...releases *automatically* when struck by tools.. re-sets *automatically* as tools go back into hole. Keeps mud and oil off of rig, steps up workmen's efficiency, saves time!

FISHING

World's deepest fishing job continues to stand at 14,366 feet—one thousand feet *deeper* than world's deepest producing well...*and a record made with Baash-Ross Fishing Equipment!* On wells of *ALL* depths, the Baash-Ross line of outstanding fishing tools continues to help operators out of tough spots—24 hours a day—in all major fields *coast-to-coast.* There's a Baash-Ross *Engineered* fishing tool for every type of job...each backed by *years* of proven dependability and effectiveness!

ON THE LOOKOUT

A NEW SUCKER ROD COUPLING is said to resist both corrosion and electrolysis. It incorporates a *replaceable* zinc "slug" which projects the steel from corrosive or electrolytic attacks. When used in place of regular steel couplings, the zinc couplings greatly reduce the harmful effect of these agents on sucker rods and tubing, it is said. **(No. 71)**

BAASH-ROSS

CALCIUM CARBIDE is being used in Ohio and West Virginia fields for removing paraffin from sand bodies at the well bottom. On coming in contact with water, the carbide generates sufficient heat to melt the paraffin and permit bailing it out. In one stripper field so treated, average production of oil was increased from 2 to 13 barrels per well per week at extremely low cost, according to reports. (No. 72)

BAASH-ROSS

TWO SEPARATE PATENTS *were recently issued on similar methods of detecting oil bearing sands while drilling. In both, the drilling mud emerging from the well is passed under ultra-violet light or similar fluorescent-exciting rays and any oil present is automatically indicated by a fluorescence detector.*

[For more information on items that interest you, simply send your name, address and key number on a post card or letterhead.]

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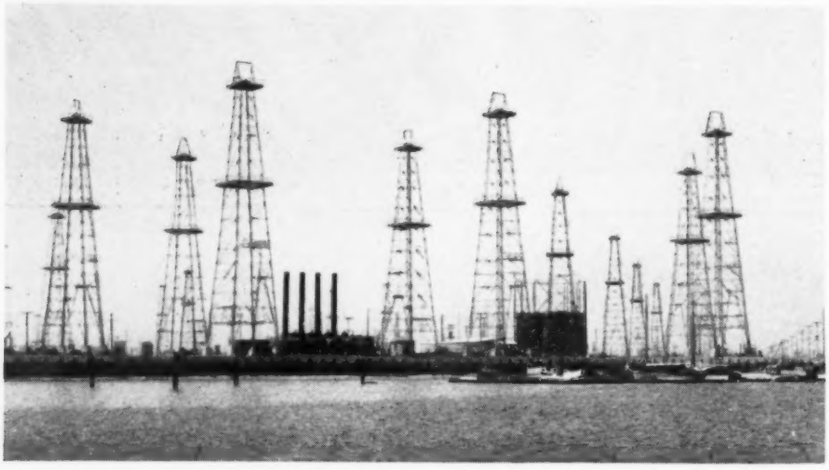


Wells spaced on the sand below this ship channel in the Long Beach Harbor district are directionally drilled from shore locations

The character of the oil being pumped is of considerable importance. Friction is the cause of wear and the lubricating properties of the oil being lifted will have its effect on the wear of rods and tubing. The proper placement of rod guides in a slant hole pumping oil with high lubricating properties may result in the tubing never being worn seriously. Even without guides the lubrication will reduce the wear.

External wear on tubing collars should not be excessive if the tubing is anchored as the movement on the casing or liner is thus made negligible. This further protects the oil string itself.

Rod collars should certainly be effectively protected by the guides. In extreme cases where guides have not been used the rod collars have been found worn until the threads show. Rod fatigue due to whipping should be less likely in slant holes.

In those installations where the rods are pulled more frequently than the tubing there is apt to be greater wear on the tubing than on the rod collars. The tubing, while lying in the same position, is subject to wear at the same place while the rods, being taken out and rerun, will probably be turned in the operation and a different side placed in contact with the tubing. Wear on the pump barrel will be on the low side.

Sand troubles are especially detrimental in slant holes as the abrasive action has more chance of becoming effective because of the constant contact caused by the well being at an angle. Furthermore, there is an increase of the amount of sand exposed as indicated by Fig. 2; although this is often advantageous from the standpoint of drainage it gives a greater area of sloughing when the sand is loosely consolidated.

Another sand hazard in slant holes completed at a large angle through the sand is the possible caving of the upper wall, which will be greater than mere sloughing of vertical walls. For this reason one company operating in Huntington Beach pulls the tubing wet. During production a small back pressure is sometimes maintained, but the bottom-hole conditions obviously govern the extent to which back pressure may be applied without detriment to production. Gas anchors, when used, also hold pressure against the sand and retard the rate of fluid pulldown.

A few wells with small deviations have been gravel packed by the use of prepacked liners in order to keep out sand. There is a possibility of more extensive use of this method of completion in areas where wells have considerable sand trouble but it would be essential to determine beforehand that the prepacked liner could be run-in without difficulty. It would appear that a well in which a prepacked liner is to be run should be drilled with that objective in mind and the course from the bottom of the casing string to the total depth should be in a straight line, continuing the inclination and direction existing at the casing point.

Surface Equipment

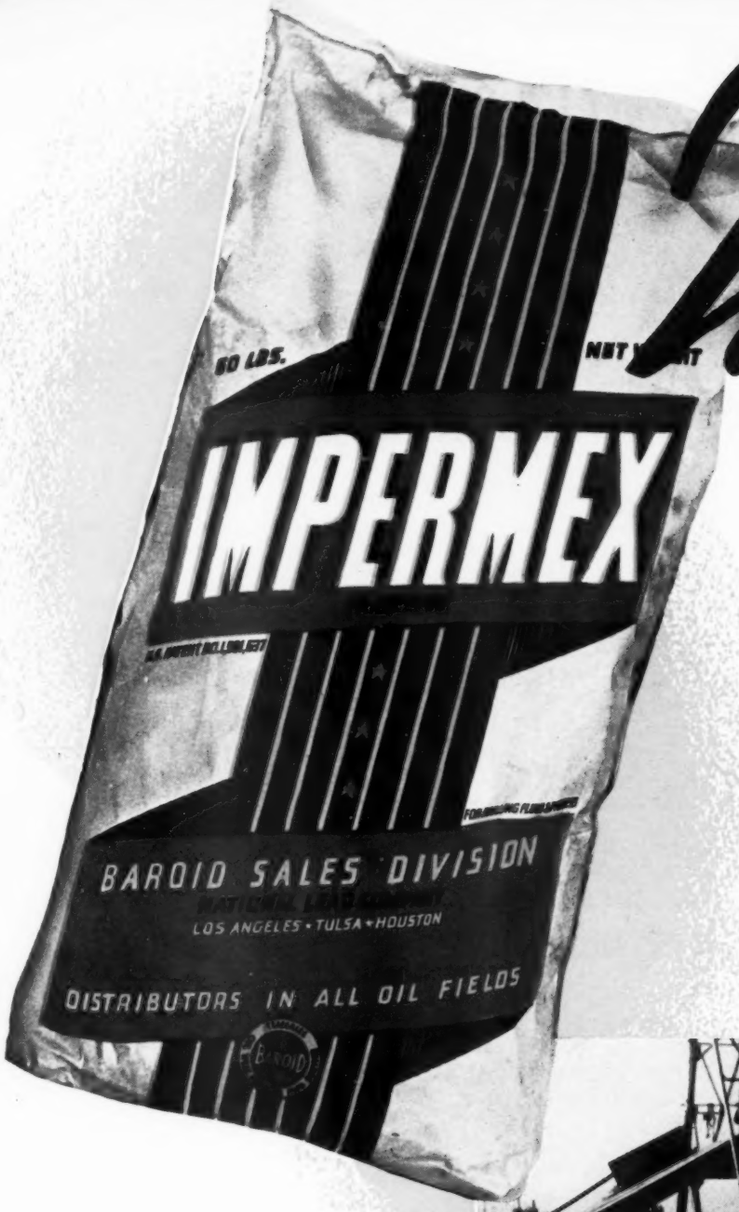
Although the surface equipment for most slant holes is selected and installed just as for any pumping well there are certain conditions that lend themselves to groupings that provide greater economies. At one pier location at Elwood, three wells were drilled at the corners of a triangle, spaced only 2 ft. apart. One well is on the center line of the derrick and the other two are equidistant from that line. When they were put on the beam for pumping, the beam for the center line well extended in one direction and the beams for the others were set parallel and extended in the opposite direction. The three holes are produced separately as individual wells.

At Huntington Beach one company is drilling tidewater wells in groups of four and five. The wells are drilled a derrick width apart in a straight line some distance back from the shore line of the ocean. A concrete slab is constructed around the group and rails set in this slab. On these rails a production derrick is moved to position over any well of the group when service work is required. The one derrick thus serves all the wells in the group and is available at all times. Concrete slabs at each well provide a foundation for a portable servicing hoist.

Conclusions

The lifting costs for pumping slant-drilled wells will probably be somewhat higher over a period of time than for well-drilled vertical wells. Not considering wear on rods and tubing it is doubtful whether these costs should be much, if any, greater than with other wells, assuming the holes are drilled with careful control of direction and full advantage is taken of equipment available for checking the performance during production. One company pumping slant holes drilled during the last two years at Huntington Beach is reported to have an exceptionally low lifting cost. It would seem that the proportion of horizontal drift to vertical depth would have a direct bearing on the lifting costs; yet some of those wells with low costs extend more than 3000 ft. below the ocean at measured depths of approximately 5000 ft.

Any conclusions concerning the pumping of slant holes must be based on the collective experience of many companies. The general opinion of field men in charge of pumping directionally drilled wells appears to be that such wells present no more problems than the average well and that subsurface conditions affect all wells to about the same degree. Tubing and rod wear is encountered in many wells of all classes and might well be less in a slant hole carefully drilled than in a vertical well put down with too much latitude for deviation from the vertical. The lubricating property of the crude oil and the effect of sand in wells making an appreciable amount of sand during production are, however, factors of greater importance in a slant hole from the standpoint of wear on subsurface equipment.



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Economics of Multiple-Zone Completions

Exclusive

☆ Reduction in number of wells drilled and accompanying saving of steel and other materials are elements that contribute to overall national conservation program

by James O. Lewis, Consulting Engineer

THE greater number of oil and gas fields have more than one horizon capable of producing oil or gas and more than half the reserves in this country are contained in such multi-zone fields. Methods for more economical and more effective exploitation of multi-zone fields are, therefore, among the important problems confronting the industry.

So far, four principles have been applied in the development of multi-zone fields:

(1) To drill separate wells to each zone.

(2) To exhaust one zone and then to recomplete into another.

(3) To produce two or more zones together through the same well.

(4) To produce two or more zones separately through the same well.

The important factors in exploiting a multi-zone field are costs and conservation. Obviously, it is to the interest of the producer to reduce his costs but the public, too, has an interest in low costs, for experience teaches by many examples that any method resulting in a reduction of costs to a considerable portion of the industry, leads to reductions in prices to the consumers. Furthermore, such reduced costs make commercially available petroleum supplies that otherwise would not be produced. Experience has shown that economics and conservation are inseparable and complementary.

The desirability to the producer of methods that will reduce the cost of drilling for and producing oil or gas in multi-zone fields is obvious. Less obvious, though of equal importance, is the favorable influence that such economies may have on the conservation of oil and gas. Among the problems of the industry is the recovery of oil and gas from the sands of lesser commercial value in multi-zone fields. Because such minor sands have, in the past, been economically unattractive, large quantites of oil and gas have been left underground. Until cheaper recovery methods are demonstrated, these latent reserves will remain unrecovered. It is to this problem of marginal sands that multi-completion methods are particularly adaptable.

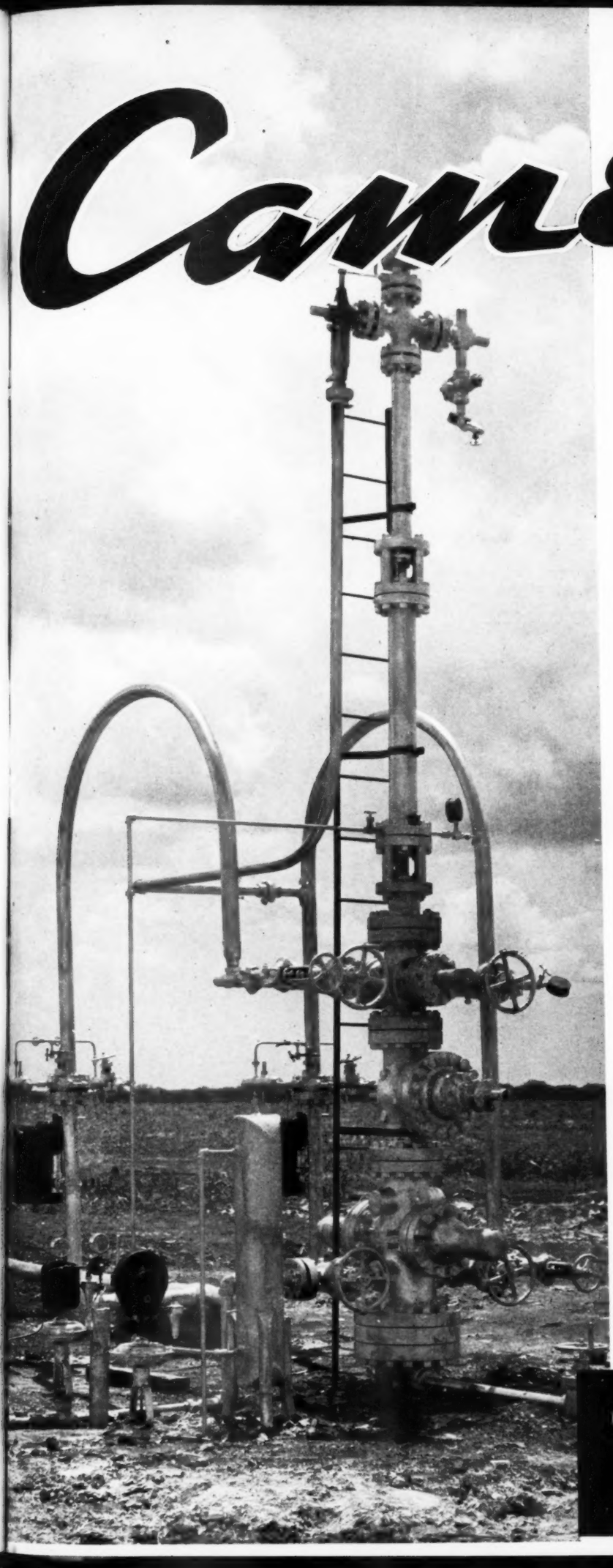
JAMES O. LEWIS

is a graduate in geology from Stanford University—After graduation spent six years in the state of California in geological and engineering work—Was with U. S. Bureau of Mines for six years, one year being spent at Muskogee, Oklahoma, in 1914-1915, introducing conservation on Indian Lands, two years at San Francisco as an investigative engineer, one year at Bartlesville, Oklahoma, as superintendent of the Experimental Station, which he founded, and two years as chief of the Petroleum Division stationed at Washington, D. C.—Left the Bureau in 1920—Was two years with Smith and Dunn, Marietta, Ohio; 18 years with Dunn and Lewis, Tulsa, Oklahoma, and is now an independent consulting engineer at Houston, Texas.

It has long been a cardinal principle of conservation that separate reservoirs in a field should be produced separately and in a multi-zone field, each zone usually constitutes a separate reservoir. The Federal Government, as well as most producing states, specifically prohibits by law connecting through the same well producing formations that naturally were separated by shale or other impervious strata. Economic considerations have limited the application of this principle and it has been found necessary to tolerate the commingling of productions from separable formations that occur closely associated in zones. It is becoming increasingly evident, however, that it is desirable to be able to separate not only different zones but in many instances the various strata composing each zone because, due to variations in permeability, water or gas advances through the several strata at different rates, thus causing operating problems that result in reduced recoveries and increased costs. Better methods for segregating formations are in the interests of both conservation and economy.

The drilling of several wells on each location in a multi-zone field separately to the various sands is a common practice. Inasfar as it results in separating the sands, the practice complies with one requirement of conservation. Being too expensive to warrant its use in the development of marginal sands, however, it also results in leaving much oil and gas underground, which aggregates a serious loss of potential supplies. Each additional well requires more steel, labor, and capital, thus increasing the cost of recovering oil and resulting in wasteful use of these other national assets.

The practice of exhausting one sand and then either deepening to another sand or recompleting in an upper sand that has been cased-off, has mechanical and practical limitations. Such limitations, however, have been greatly reduced by recently developed well-completion practices, among them being the method of drilling through the sands, cementing them off behind the casing and then opening them later through gun-perforations or by drilling windows through the casing. The method has the advantage of permitting the zones to be produced separately, but it also has the disadvantage of causing either the premature abandonment of the first zone or the deferment of development of the minor zones far into the future; frequently the operator neglects to develop the minor zone and may even forget its existence. When, however, either the principal sand is naturally short-lived or the gas is quickly cycled out, as in gas-condensate fields, the method is satisfactory. Proration, by prolonging



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The adaptability of Cameron equipment to any special method is illustrated by the photograph at left. The Xmas Tree manifold on this high pressure gas distillate well, one of numerous "double barrel" completions in the Agua Dulce (Texas) field, employs two Cameron Ram-Type Tubing Control Heads. A Cameron Type "G" Circulating Anchor Packer and the Lewis Bottom Hole Transfer Valve and Actuating Device permits flowing, gas lifting, or pumping two sands selectively. The latter is manufactured by Cameron Iron Works, Inc., under exclusive license from James O. Lewis.

Interested operators are invited to consult with Cameron engineers who have gained wide experience from pioneering multiple zone completions.

CAMERON IRON WORKS, INC.

Three sets of surface equipment to produce three separate zones become an extravagance when multiple-zone completions are employed

the lives of the wells, has reduced the applicability of the method.

The method of producing several zones together through the same well has the virtues of low cost, of increasing the daily production, and, where conditions are suitable, of reducing the operating expense per barrel. On the other hand, it violates the conservation ruling that separable sands shall be produced separately. It is now generally recognized, of course, that the practice of connecting sands does not of itself cause waste; that under certain natural conditions and manners of operation, sands can be produced together without undue waste. Nevertheless, occurrences of such favorable conditions are limited and in the majority of instances, the practice is objectionable.

Before scientific principles had been applied to oil and gas recovery, the operator endeavored to produce from as great a thickness of producing formation as was mechanically feasible. He was limited by the troubles from cavings that came into the hole from shales separating the producing formations or by intervening water, gas, or thief sands. Modern methods of using cemented casing containing gun-perforations or drillable windows have increased the practicability of producing different horizons together. Better control can be exercised when these methods are employed, but the conditions under which these practices can be conducted without unduly violating conservation rules are still quite limited. The practice has had a revival in the Illinois fields, where it is not prohibited by conservation laws and where natural conditions make the practice less objectionable than in most other fields.

The completion of wells so that the fluids (oil and/or gas) produced from two or more sands can be conducted separately to the surface is an old practice, particularly when the upper sand produced dry gas. In drilling wells by cable tools, upper sands were frequently confined between two strings of casing so that the oil contained in the upper sand could flow separately to the surface through the annulus if the pressure and volume of the gas were sufficient to lift the liquids and remove the cavings. As the conditions necessary for flow often had never existed, or if they did exist early in the life of a well, had never continued for long, the method was not satisfactory, and it resulted in leaving most of the oil or gas unrecovered in the upper sand. Similarly, when a packer has been set and a string of tubing is used to separate two sands, it has not been satisfactory to depend on natural flow to lift the liquids and remove the cavings from between the tubing and the casing. For successful production through the annulus, methods were needed whereby the liquids and solids could be more effectively removed and production continued until the sands were commercially exhausted.

The same practices of employing cemented casing containing gun-perforations or windows that have aided in producing multi-zone fields have also facilitated the development of methods for producing sands separately through the same well. In one method, one or more packers are placed in the well between the perforated sections or windows in the casing and tubing strings are run through the packers in such a way that two or three sands can be flowed separately. The equipment is designed so that the tubing can be removed readily or unseated in case flow ceases through either annulus.

The same type packer is adapted for use with tubing and pump. In Kansas, the packer is set between the Arbuckle Lime and the Kansas City Lime and the tubing can be moved through the packer so that a perforated portion of the tubing is either above or below the packer, thus permitting oil to be pumped alternately from the two horizons. The practice is to pump from the Arbuckle Lime for half the month and from the Kansas City Lime for the other half of the month. There is no gas escape from the Arbuckle Lime but as the formation is produced at a pressure above solution pressure for the gas, no difficulty is experienced in pumping the oil. When more gas accompanies the oil, difficulties may be expected.

On the Gulf Coast, two other methods are in use. A packer on a tubing set in the casing between two perforated sections provides two separate flow paths to the surface. A smaller inner tubing is also set with valves arranged whereby the inner tubing can be selectively connected with either annulus. In one arrangement, the valve is operated from the surface and in the other by running in a tool on a wire line. One of the devices has so far only

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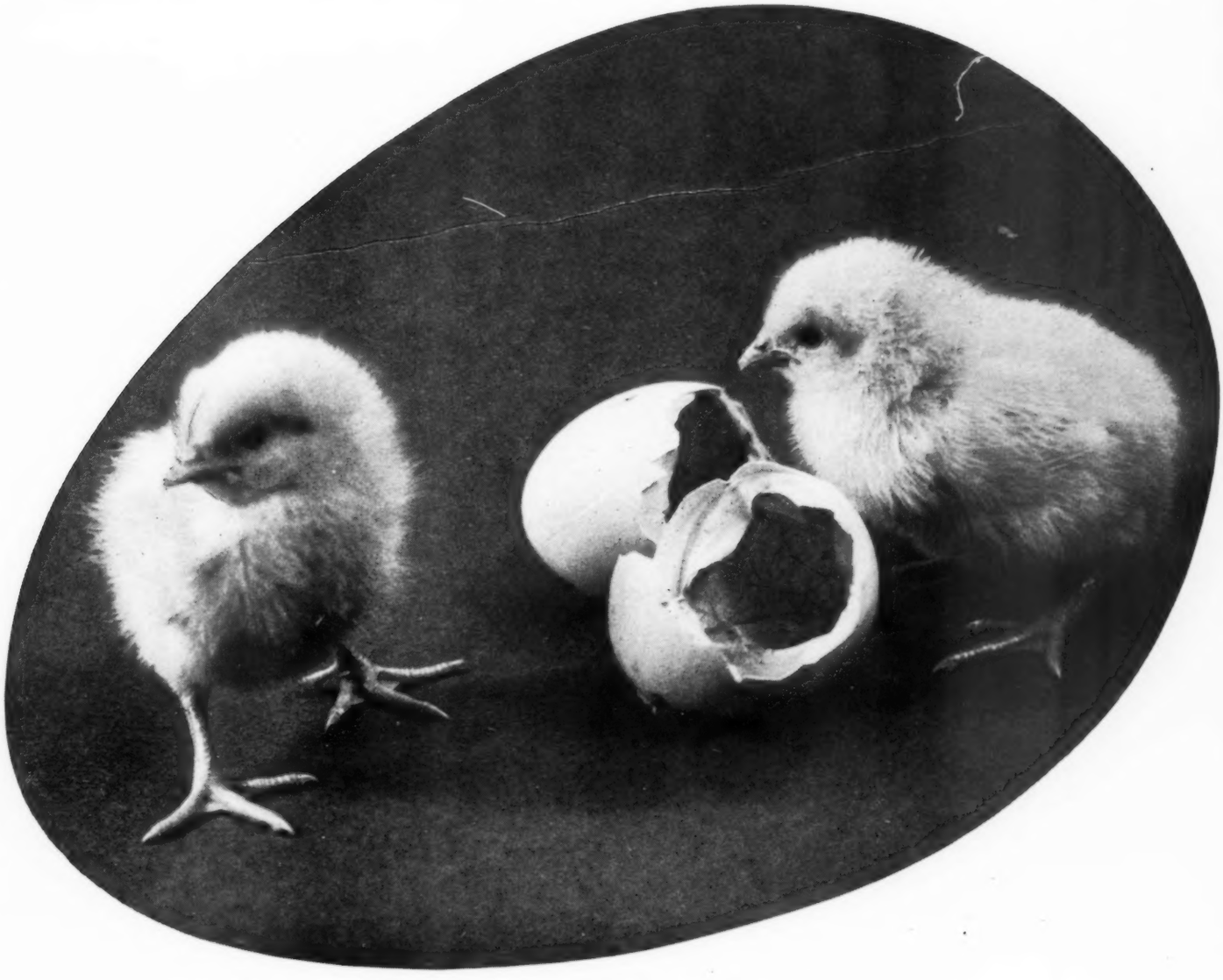

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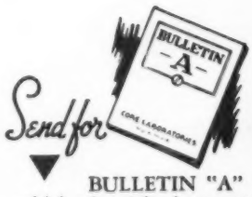

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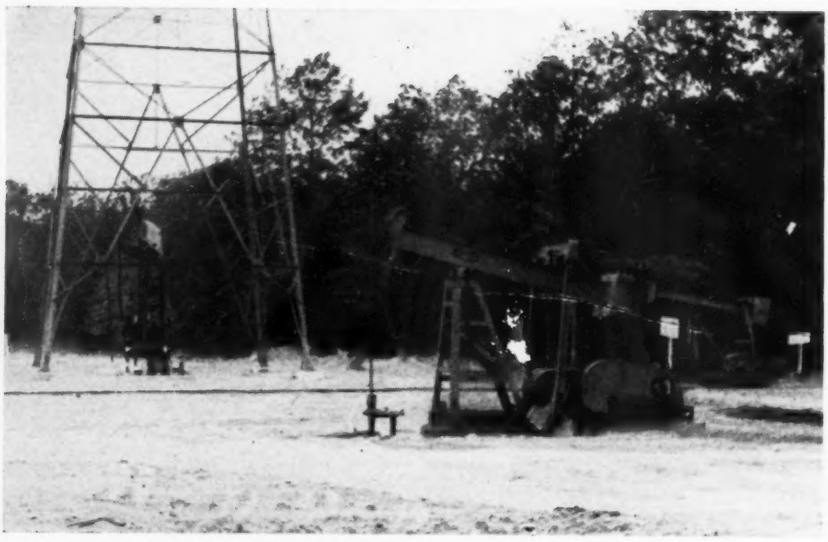

Three pumping units on one location in Salem field, Illinois

been used on condensate wells. The devices can be adapted to pumping or gas-lifting oil.

Both the method of producing two sands together as practiced in Illinois and the method for producing two sands separately as practiced in Kansas, in the Gulf Coast, and in California, have been referred to as "double-completions," yet it is obvious that they are unlike and should have different terms. In this article, double, triple, or multi-completion of oil or gas wells refers only to methods wherein the sands are separated and their productions conducted separately to the surface.

It is evident that devices incorporating the principle of producing from two sands separately through the same well best meet the two requirements of economy and conservation, yet in fields where there are many sands, it will still be necessary either to drill more than one well at each location or to exhaust sands in succession even though multi-completion devices are used, because at most only three sands can be produced through the same well and often only two. Where the wells will have long lives, as is the case in most oil fields, it will be desirable to drill more than one well on a location if all the worthwhile sands cannot be produced in one multi-completed well. Where each sand can be exhausted quickly, as in most gas-condensate fields, the tendency will be to drain the sands and then to recomplete into other sands.

Proration laws and practices have recently stimulated interest in multi-completion methods. The continued reductions in well allowables have reduced the rates of return upon investment and have decreased ultimate profits. It has thus become highly desirable to reduce the ultimate cost per barrel of oil recovered and to increase the current rate of return. Solution to these problems has been sought in three principal directions; wider spacing, "slim-hole" drilling, and other drilling economies, and more recently, in multi-completions. These three approaches are not necessarily alternatives; depending on local conditions, they can be employed conjunctively.

Proration has also removed some objections that formerly would have been made to multi-completions of oil wells. Not so much daily production can be taken from two sands through one dual-completed well as through separate wells to each sand. In the days of unrestricted production and competitive drainage, an operator would not have wanted to reduce the productive capacity of his property during the flush stages by double completions, but with the present small allowables this is no longer an objection, inasmuch as the allowables for both sands can readily be taken through a single well. Another objection that has more recently been removed is that of basing allowables upon actual production tests that necessitated the maintenance of the well in condition to produce at its maximum capacity from each sand during the infrequent potential tests. The question of how allowables are to be made to multi-completed wells by proration authorities has not been fully worked out, however, and the use of the method will be greatly influenced by the rules adopted for its control.

The comparative costs of developing a property by twin wells or by double completions will vary principally in accordance with the differences in depths to the two sands, with the devices being used, and with whether the same surface equipment can be used for both sands. Costs are available from three localities where devices are in use that will permit production from both sands to be pumped or gas-lifted when necessary so that the sands can be depleted down to low pressures.

A. S. Ritchie[1] supplies the following information on practices in Kansas where double completions have been made on four wells producing from the Kansas City Lime at 2900 ft. and the Arbuckle Lime at 3200-50 ft. The wells are drilled "slim-hole" and are completed with 5½-in. oil string. They use the same pumping equipment and tank battery and are equipped with a string of tubing and a packing device that permits alternate pumping of each sand. Twin wells in this locality cost $36,000 to $38,000 whereas a double completion can be made for $22,000, a saving of $14,000 to $16,000 at each location and a comparative cost of 61 to 58 percent. Ritchie states that lifting expense per barrel is much less for double completed wells.

In the lower Gulf Coast area, double completions have been applied to several wells in two gas-condensate fields. The method is to use a 4¼-in. casing with a packer set between two sands and a small inner tubing that can be connected alternatively to unload each annulus, the valve being operated by a timing mechanism at the surface. The gas from the two sands is gathered through the same surface lines. The fields have numerous sands ranging from 4800 to 6500 ft. in depth and sands at various horizons have been produced by the device through the same well.

Figures supplied by E. C. Will[2] show that the additional equipment for a double completion costs $4500, which is to be set against the cost of an additional well. In one of the fields, a double completed well costs $67,500, whereas the estimated cost of two wells to the same sands is $122,500, a difference of $55,000 and a comparative cost of 55 percent. In one field alone, the savings in drilling costs will total well over $1,000,000.

In a deep Gulf Coast oil field, another device is being successfully employed. According to E. O. Bennett,[3] the additional cost of double complet-

[1]McPherson Drilling Company, Wichita, Kansas.
[2]LaGloria Corporation, Corpus Christi, Texas.
[3]Continental Oil Company, Ponca City, Oklahoma.

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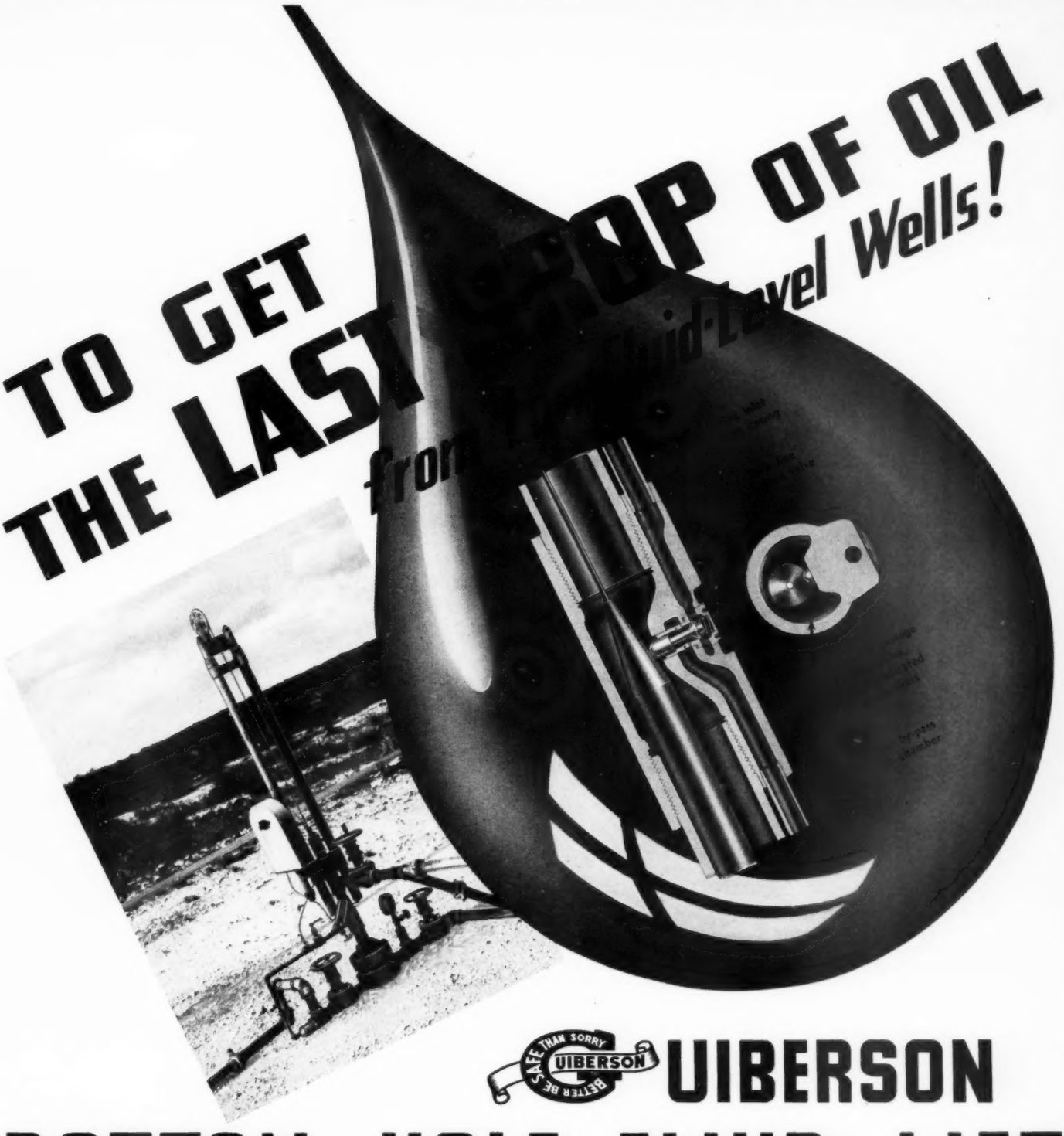

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ing in this field is $3000 and the cost compared to separate wells is less than 55 percent. Production is now flowed but the device is adaptable to pumping when the time comes.

Figures on savings in other localities are not at hand, but it is evident that in general double completed wells will save more than 40 percent in comparison with the cost of twin wells.

Savings in production expense will also be important as it will be cheaper to operate one double completed well than two wells at the same location. For gas-condensate wells, the savings will not be large, for such wells require little attention, but for oil wells, particularly pumping wells, the savings will be large and the per barrel production expense should be nearly halved. The saving that can be effected, however, will depend largely upon what allowables are permitted for double completed wells.

To illustrate the possible savings that can be gained from double completions, three examples based upon assumed but reasonable conditions are given in Table 1.

Although these examples are hypothetical, they illustrate the manner in which double completions operate to reduce costs, increase returns upon investments, and make possible the development of leaner sands that otherwise might never be produced. It can, therefore, be viewed, when properly applied, as tending to conserve oil and gas by making available latent reserves. Moreover, conservation should not be narrowly viewed from the sole standpoint of oil and gas, for other national resources are involved in the recovery of oil and gas such as man hours of work, iron, and coal. The conservation of steel supplies at this moment appears more pressing than the conservation of oil and gas and the industry has been asked to reduce its requirements. Double completions will save from 25 to 40 percent of pipe and other equipment.

Methods for multi-completion of wells in such manner that production can be carried beyond the flowing stage are a recent development, but so far they have been applied to only a few wells though covering a wide range in conditions including shallow pumping wells in Kansas, gas-condenstate wells 6500 ft. deep in Texas, and oil wells 9000 ft. deep in Louisiana. How far it will be practical to extend the use of these devices cannot be foretold at this time. It may be expected that difficulties and objections will be encountered but it is also probable that improvements in methods and devices will be made that will overcome many of the difficulties and objections. The limitations will have to be determined from experience.

There will also be proration problems: Under what conditions will multi-completions be permitted? Will a double completed well be given an allowable equal to two separate wells to the same sands? How can the proper use of double completions be assured? It can be expected that the proration authorities will take a constructive attitude toward solving these problems so as to foster and not to frustrate a method that promises so much for economy and conservation.

TABLE 1

The first example assumes the conditions and costs given by A. S. Ritchie.

Assumptions:

Kansas City Lime well: Recovery, 2000 bbl. per acre; spacing, 20 acres; well cost, $17,000; oil price, $1.15 per bbl., and production expense, 50 cents per barrel.

Arbuckle Lime well: Recovery, 5000 bbl. per acre; spacing, 20 acres; well cost, $20,000; oil price, $1.15 per bbl., and production expense, 40 cents per barrel.

Double completion: Recovery, 7000 bbl. per acre; spacing, 20 acres; well cost, $22,000; oil price, $1.15 per bbl., and production expense, 75 percent of the expense when twin wells are drilled.

Estimated profits:

Twin wells	Well costs	Net income	Profit Dollars	Profit Percent
Kansas City Lime	$17,000	$ 26,000	9,000	53
Arbuckle	20,000	75,000	55,000	275
TOTALS	$37,000	$101,000	64,000	173
Double completion	$22,000	$116,000	94,000	472
Gains	$15,000	$ 15,000	30,000	254

The second case assumes two sands, neither of which would yield a satisfactory profit from separate wells except during periods of high prices.

Assumptions:

Upper sand: Recovery, 2500 bbl. per acre; spacing, 20 acres; well cost, $30,000; oil price, $1.00 per bbl., and production expense, 50 cents per barrel.

Lower sand: Recovery, 4000 bbl. per acre; spacing, 20 acres; well cost, $40,000; oil price, $1.00 per bbl., and production expense, 40 cents per barrel.

Double completion: Recovery, 6500 bbl. per acre; spacing, 20 acres; well cost, $43,000; oil price, $1.00 per bbl., and production expense, 75 percent of the expense when twin wells are drilled.

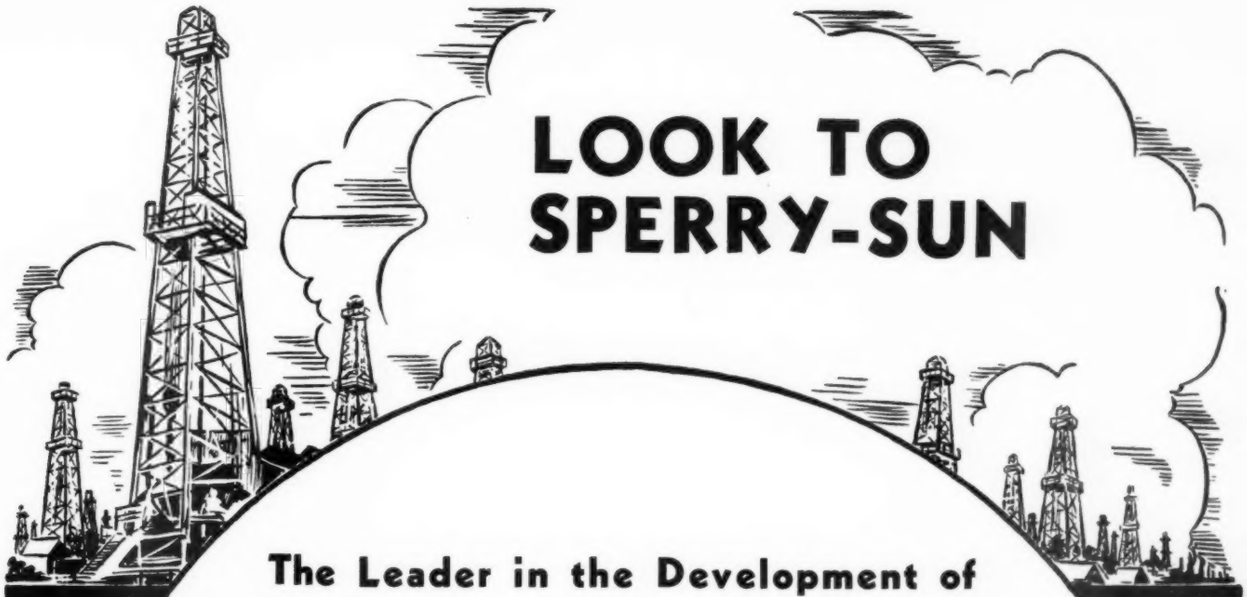
Estimated profits:

Twin wells	Well costs	Net income	Profit Dollars	Profit Percent
Upper sand	$30,000	$25,000	—5,000	—16.7
Lower sand	40,000	48,000	8,000	20.
TOTALS	$70,000	$73,000	3,000	4.3
Double completion	$43,000	$87,000	44,000	102.
Gains	$27,000	$14,000	41,000	98.

The third illustration assumes two deep but rich sands.

Estimated profits:

Twin wells	Well costs	Net income	Profit or loss Dollars	Profit or loss Percent
Upper sand	$ 60,000	$300,000	240,000	400
Lower sand	70,000	400,000	330,000	470
TOTALS	$130,000	$700,000	570,000	438
Double completion	$ 74,000	$745,000	671,000	907
Gains	$ 56,000	$ 45,000	101,000	469



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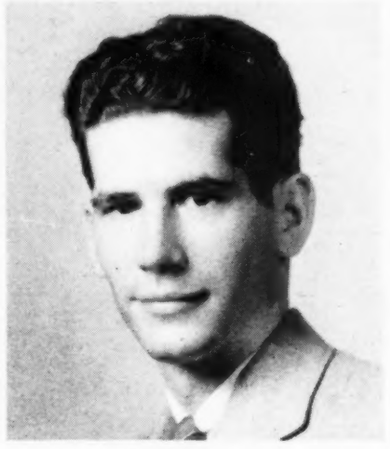
By P. G. Shelley, J. B. Stone, and L. W. Colburn
Dowell Incorporated

P. G. SHELLEY

attended University of Missouri and University of Oklahoma—Received B.S. degree in petroleum engineering from the latter in 1928 and M.S. in 1929—From 1929 to 1931 was instructor of oil and gas production at Pennsylvania State College, and was associated with field research in Bradford area—From 1931 to 1936 was employed as research chemist by Phillips Petroleum Company at Okmulgee, Oklahoma—Since October, 1936, has been with The Dow Chemical Company as research chemist and petroleum engineer.

Abstract

Calcareous cores from three formations have been acidized in the laboratory under conditions whereby the entire core was maintained under a pressure comparable to well pressures during acidizing and comparisons made with cores acidized at or near atmospheric pressure. The authors conclude that the presence of undissolved CO_2 in low-pressure laboratory treatments results in channeling of the acid through larger pores and higher indicated acidizing indices than obtained under high pressures. Under high pressure, the acid distributes itself more evenly in the pores and passes through the core in less time. Composition and structure of the formation and original permeability are shown to have marked effect on the acidizing index.



J. B. STONE

received A.B. degree from University of Indiana in 1932; M.S. degree in chemistry and geology in 1933; following this, took additional graduate work at University of Indiana—Was employed from August, 1936, to July, 1937, as a research chemist by The Dow Chemical Company of Midland, Michigan—Has been chief chemist with Dowell Incorporated from July, 1937, to the present time.

SINCE 1932 when acidizing was being introduced to the oil industry as a means of increasing production from wells, a great amount of interest has developed in laboratory work that would demonstrate the action of acid on various formations. This work originally was confined to solubility tests, but more recently the laboratory acidization of cores has assumed greater importance.[1,2,3] Data obtained from this core work may be used either for predicting results to be expected from acidizing or for diagnosing a well for treatment or in the development of special acids to meet special conditions in wells.

Previously published work on core acidizing has been carried out either at or near atmospheric pressure. Although this work is no doubt of unquestioned value, in most cases it does not simulate the conditions found during an actual acid treatment. In a treatment, the acid at the point of reaction at the bottom of the well is always at a pressure in excess of atmospheric pressure. This is the result of bottom-hole pressure, plus any excess hydrostatic pressure due to filling the tubing with acid, plus the pump pressure applied at the surface.

The purpose of the work described in this article is to compare data obtained by acidizing cores under low-pressure conditions with that obtained by acidizing cores under substantially higher pressures. To accomplish this it was necessary to design and construct apparatus suitable for maintaining several thousand lb. per sq. in. on the low-pressure side of a core, while applying a still higher pressure to the upstream side, thus creating a differential pressure for forcing the acid through the core.

During the progress of this work, approximately 80 cores from three sources were treated: (1) Niagaran dolomite from a quarry near Woodville, Sandusky County, Ohio; (2) oölitic Bedford limestone from a quarry near Bedford, Indiana; and (3) oölitic McCloskey limestone from producing wells in the Clay City and Noble pools of the southern Illinois basin. These rocks were chosen for their comparative uniformity and availability. Analysis shows the Niagaran to be almost pure limestone. Table 1 lists the data on Niagaran dolomite cores treated at three pressures; Table 2, the data on Bedford limestone cores, and Table 3, the data on McCloskey cores.

Cores were treated at gauge pressures of three magnitudes: approximately atmospheric or zero, 1250, and

[1]Plummer, F. B., and Newcome, R. B., Jr.: "Laboratory Investigation on Acid Treatment of Oil Sands." A.I.M.E. *Petroleum Development and Technology, 1936*. p. 100.

[2]Chamberlain, L. C., Jr.: "Acidizing Core Samples," *The Oil Weekly*, February 28, 1938.

[3]Fitzgerald, P. E., James, J. R., and Austin, Ray L.: "Laboratory and Field Observations of Effect of Acidizing Oil Reservoirs Composed of sands, *A.A.P.G. Bulletin*, Vol. 25, No. 5, May, 1941.

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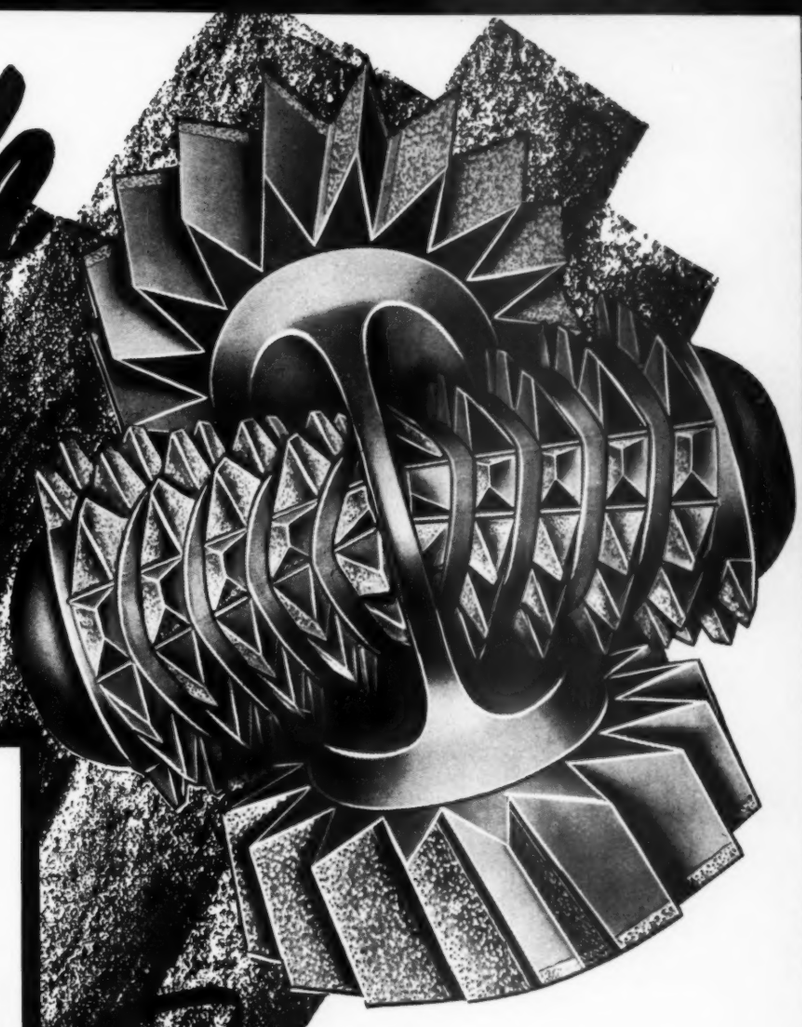

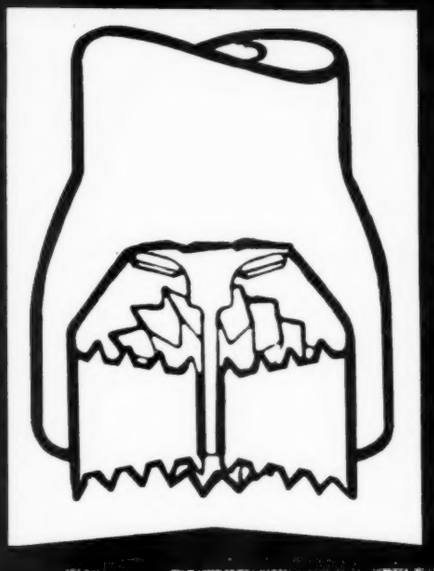

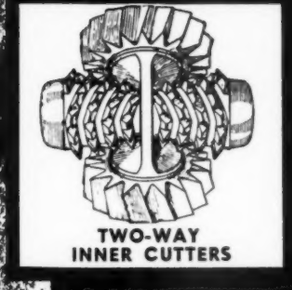

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L. W. COLBURN

received technical training at General Motors Institute of Technology — Did field seismographic research work for Western Geophysical Company in California in 1936—Laboratory technician for The Dow Chemical Company from 1937 to present time.

2500 lb. per sq. in. on the downstream end of the core, with pressures from 100 to 200 lb. per sq. in. higher on the upstream end to create a treating differential. Data on only about half the cores tested are included in the tables, as difficulties with the apparatus and other factors negated the results obtained on the other half. Data on cores treated at atmospheric pressure are presented for comparison. Although all tests to date have been made at room temperature, provision for temperature control has been incorporated into the apparatus and controlled temperature tests are contemplated.

Apparatus

Two distinct means of pressure control were used in obtaining the data presented in this article. Fig. 1 shows diagrammatically the first method; Fig. 2 and the photograph, Fig. 3, show the second and preferred method.

Only the data in the 1250-lb. pressure range were obtained on the apparatus shown in Fig. 1. With reference to this figure the system operates briefly as follows: The pump, *J*, circulates the pressure fluid through the relief valve, *G*, back to its own suction. The differential pressure exerted across the core in the chamber, *A*, was the pressure for which the relief valve, *G*, was set—either 100 or 200 lb. per sq. in. The upstream pressure was exerted upon the sand filter, *F*, and the acid reservoir, *B*. The fluid going through the core returns to the pump suction through the flow meter, *E*. An external pressure is held on the system by the tandem hydraulic and gas cylinders, *H* and *I*. This pressure is controlled by means of a regulating valve (not shown) operating from a cylinder of nitrogen. The ratio of the area of the two cylinders is such that 10 times the pressure in the gas cylinder was exerted on the system. It is necessary to rotate the two pistons continually to insure smooth operation and even pressure. The fluid inventory in cylinder *H* serves to take care of any leaks. The pump used in this set-up is a Hills-McCanna dual unit proportioning pump, capable of delivering 200 cc. per min. at pressures as high as 4800 lb. per sq. in.

The apparatus on which the data at 2500 lb. per sq. in. were taken is shown diagrammatically in Fig. 2. Referring to this figure, the pressure medium is circulated by pump *F* from the atmospheric-pressure oil reservoir, *J*, through the two relief valves, *H* and *G*, connected in series, and back to reservoir *J*. Relief valve *H* serves to regulate the differential pressure across the core (100 or 200 lb. per sq. in.) and relief valve *G* maintains the downstream pressure on the core (2500 lb. per sq. in.) and discharges fluid back to atmospheric pressure. Fluid forced through the core as a result of the pressure drop at *H* returns through flow meter, *E*, and relief valve, *G*, to the reservoir, *J*. A differential gauge, *D*, indicates, the pressure drop across the core in both systems.

Fig. 3 shows a general view of the high-pressure apparatus. *A* is the core chamber; *B* is the acid reservoir in which acid is placed prior to the treatment; *C*, the spent acid receiver; *D*, the differential pressure gauge; *E*, *F*, flow meters; *G*, the main relief valve in the pump bypass maintaining the desired pressure on the entire system; and *H* is the relief valve that controls the differential pressure. The pump, which circulates mineral seal oil as the pressure medium, is situated behind the panel. It is a $\frac{9}{16}$-in. by $1\frac{3}{8}$-in. triplex, capable of delivering approximately 50 gal. per hr. at 5000 lb. per sq. in.

Several units of the apparatus required special consideration. First among these was the core holder; because the ordinary type of beveled rubber stopper clamped into a correspondingly beveled metal retainer failed to operate satisfactorily at high pressure, it was necessary to redesign the holder. Cores 1 in. in diameter by approximately 1 in. in length were used. In the core holder finally adopted, the core is placed on a perforated pedestal 1 in.

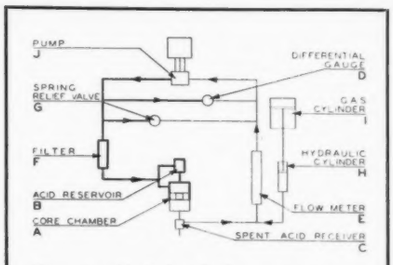


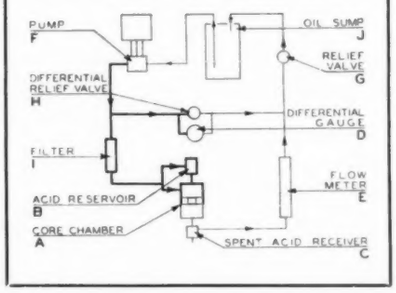
Fig. 1. Sketch of the apparatus used in procuring 1250-lb. data

in diameter and about ¾ in. in height, which is an integral part of a lower flange. A piece of Neoprene tubing somewhat longer than the core is stretched over both core and pedestal. A flanged hood comprising the upper half of the chamber comes down over the core and pedestal and the flanges are bolted together. Pressure in the upper chamber tends to seal the tubing around the sides of the core and pedestal, and fluid is forced to flow through the core from end to end.

In order to determine the time when the first acid came through the core and also the time when all acid was through and oil flow resumed, an electrode, insulated from the apparatus, was placed in the fluid passage directly under the core. This electrode was connected through batteries to a light, which became illuminated when a conducting fluid was in contact with the electrode.

Determination of the volume and rate of flow through the core was one of the most serious difficulties. Two types of flowmeters are mounted in the present apparatus. One consists of a ½-in. stainless steel pipe mounted horizontally, having a capacity of 100 cc. and calibrated at 1-cc. intervals. Inside this pipe is a piston with leather cups on either end and a small magnet attached. Fluid flowing through the core displaces this piston along the tube and its position is followed with a small compass. When the piston reaches the

Fig. 2. Sketch of the apparatus used in procuring 2500-lb. data



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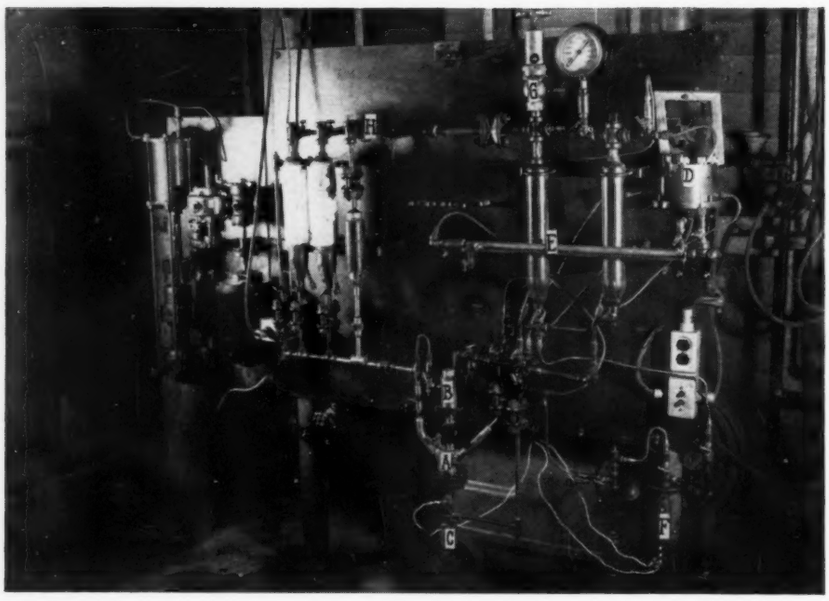

Fig. 3. Laboratory set-up of the high-pressure apparatus
(Symbols A, B, C, D, E, F, and H are referred to in the text)

end of its travel, it is forced back by temporarily reversing the flow. The other flowmeter consists of a U-tube containing a conducting liquid. The downstream leg of the U is fitted with 5 electrodes at varying distances. The volume between these electrodes, each of which closes a circuit containing a lamp when shorted to the walls, is a known quantity. Oil displaced by fluid passing through the core is routed into the upstream side of the U and forces the conducting fluid into contact with these electrodes one after the other. Observation of the time between the appearance of the various lights allows calculation of the rate of flow. Means for equalizing the conducting fluid is provided.

The only other apparatus feature of special interest is the differential pressure gauge. The working parts, including bourdon tube, linkage, etc., from a 300-lb. gauge are mounted in a steel case capable of holding the maximum total pressure. The top of this case is made of non-magnetic material (stainless steel). The needle is removed from the gauge works and in its place a small horseshoe magnet is mounted on the pin with its open end pointing upward and extending just below the stainless steel top of the case. On top of the case the gauge dial is mounted and the position of the magnet is indicated by a compass needle, which indicates on the gauge dial in the same manner as an ordinary gauge needle. The upstream side of the core is connected to the bourdon tube and the downstream side is connected to the space inside the case, surrounding the bourdon tube. Pressure drop across the core is indicated directly on the dial.

Four-normal HCl (13.7 percent) containing an inhibitor and a demulsifying agent was used in all tests.

Each core, after being drilled parallel to the bedding and cut to length, was extracted with an acetone-ether mixture, dried and weighed. Its permeability was determined using air and the core was then mounted in the apparatus. Treating pressures were adjusted and a flow rate at the chosen differential pressure was taken with the mineral-seal oil used as a pressuring fluid. Then acid was admitted to the core chamber and the time noted for the first drop to come through. The time for the entire charge of acid to come through was then noted and oil allowed to continue to flow through the core and another oil rate taken. The pressures remained the same throughout this entire cycle. Acid was then drained from the spent acid receiver, the pressure released, and the core removed. Following this, it was again extracted, dried and weighed, and its permeability determined. Also, the normality of the spent acid was determined.

Atmospheric-pressure treatments were made on a different apparatus comprising a horizontal core holder of the beveled rubber stopper type having an acid reservoir on the upstream side of the core and a drain on the downstream side. The acid reservoir was equipped with means for maintaining steady air pressures as high as 100 lb. per sq. in. on the fluid in the reservoir. The sequence of operations was the same as with the high-pressure treatments.

Analysis of Results

Three criteria were chosen as bases for comparisons. These are: (1) the acidizing index, which is the percentage permeability increase divided by the percentage weight loss; (2) the treating factor, which is defined as:

$$\frac{V}{KtP} \times 10^8, \text{ where}$$

TABLE I
Acid treatment of Niagaran dolomite cores

No.	Pressure, lb. per sq. in., gauge		Time, min.	Acid volume, cc.	ΔN	Weight loss		Permeability, millidareys			Acidizing index	Treating factor
	Upstream	Downstream				Grams	Percent	Before	After	Percent increase		
1	100	0	9	10	.....	2.375	6.33	277	350	26.4	4.17	0.067
2	100	0	13	10	.....	2.270	6.05	263	324	23.2	3.84	0.049
3	100	0	16	10	.....	2.417	6.45	250	390	56.0	8.68	0.042
4	100	0	7	10	.....	1.662	4.56	263	405	54.0	11.80	0.091
5	100	0	16	10	3.5	3.327	9.0	38	230	505.0	56.00	0.274
6	100	0	15	10	3.3	2.028	5.45	142	256	80.0	14.70	0.078
7	100	0	8.75	10	3.3	1.745	4.41	95	364	283.0	64.00	0.201
8	100	0	12.00	10	3.7	3.112	8.41	412	412	0.0	0.00	0.034
9	Average		12.09	10	3.5	2.367	6.33	218	341	128.5	20.4	0.105
10	1290	1190	4.41	13.5	2.34	2.724	7.25	175	325	85.7	11.80	0.291
11	1290	1190	2.41	7	1.97	1.551	4.02	100	115	15.0	3.60	0.482
12	1390	1190	3.0	7	3.42	1.594	4.24	90	95	5.6	1.31	.....
13	1310	1210	4.0	11	3.5	2.011	5.50	135	162	20.0	3.64	0.339
14	1290	1190	5.0	12	3.3	3.328	8.70	89	135	51.6	5.95	0.449
15	1290	1190	2.0	11	3.6	1.981	5.31	131	165	25.8	4.87	0.699
16	1390	1190	2.16	10	3.2	1.421	3.73	65	71	9.2	2.47	0.592
17	1390	1190	3.0	13	3.1	1.876	4.89	84	95	13.0	2.65	0.429
18	Average		3.25	10.6	3.05	2.061	5.46	94	127	30.1	4.50	0.469
19	2600	2500	6.0	10	2.6	1.599	4.12	93	100	7.5	1.82	0.297
20	2600	2500	5.0	12	3.3	1.594	4.25	114	120	5.3	1.24	0.351
21	2600	2500	4.0	8	3.4	1.357	3.60	112	120	7.1	1.97	0.298
22	2600	2500	4.16	10	3.0	1.322	3.43	115	130	13.0	3.79	0.347
23	2600	2500	5.0	10	3.3	1.024	2.68	100	130	30.0	11.20	0.333
24	2600	2500	4.25	13	3.2	1.926	5.13	115	192	67.0	13.04	0.427
25	2600	2500	3.05	12.5	3.0	1.456	3.8	140	165	17.9	4.70	0.488
26	2600	2500	2.33	13	3.6	2.128	5.68	140	250	78.5	13.80	0.673
27	Average		4.22	11.1	3.2	1.551	4.09	116	151	28.3	6.45	0.402

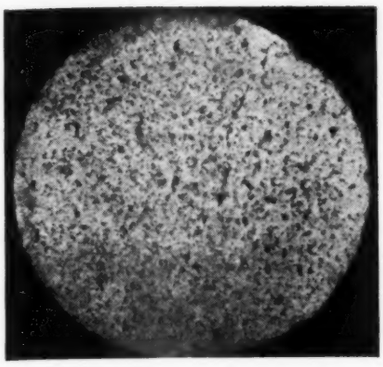

Fig. 4. Niagaran dolomite acidized at 1250-lb. pressure

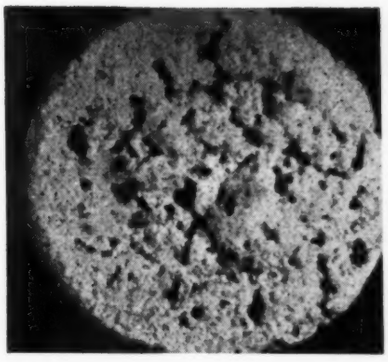

Fig. 5. Niagaran dolomite acidized at atmospheric pressure

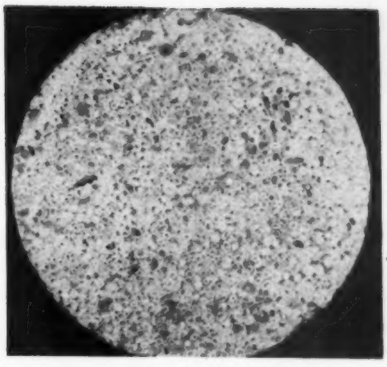

Fig. 6. Bedford oolitic limestone acidized at 1250-lb. pressure

V = volume of acid in cc.

K = original permeability in millidarcys

t = time for acid to flow through core in seconds

P = differential pressure across the core in lb. per sq. in.

and (3) the general appearance of the core after treatment.

The acidizing index indicates the effectiveness of rock removal by the acid in producing added permeability and the treating factor is an indication of the ease with which acid finds its way into and through the core during treatment. Other headings in Tables 1, 2, and 3 are self-explanatory with the exception of $\triangle$N, which is the normality change brought about in the acid during its passage through the core.

Acidizing indices[2] show a tendency to be reduced by high pressure on the core during treatment. This would be expected inasmuch as higher permeability results when a given amount of rock is dissolved from a relatively small number of pores, as occurs when the acid creates channels in the rock, than when the rock is uniformly removed from a matrix of very small pores. The evidence here is not conclusive, however, as other factors have an important influence on the acidizing index. Among these factors are: (1) the rock itself as related to its composition and structure and (2) the original permeability. Low-permeability cores show higher acidizing indices and are also more likely to show decreased acidizing indices as a result of increased pressure.

Acidizing indices are very largely a characteristic of the rock involved. On Niagaran dolomite shown in Table 1, the range is 1.24 to 64.0; on the Bedford and McCloskey limestones, shown in Tables 2 and 3, respectively, the range is from 466 to 31,600.

The next most important variable affecting this index is the original permeability of the core. High initial permeability results in a low acidizing index and vice versa. When these variables are eliminated, however, by considering results on cores from the same formation having similar permeabilities, it becomes evident that in general the high-pressure treatments have resulted in slightly lower acidizing indices than the atmospheric-pressure, which is still somewhat higher than the averages at other pressures.

The Bedford cores, Table 2, indicate this influence of high pressure on overall averages. When the data are grouped for cores having original permeabilities of more than 50 millidarcys and those having original permeabilities of less than 50 millidarcys, it becomes evident that the low permeability cores demonstrate this phenomenon to a marked degree. The average acidizing index at atmospheric pressure is 12,497; at 1250 lb. per sq. in. it is 7533; and at 2500 lb. per sq. in. it decreases to 3769. The higher permeability cores do not check out so well, the average acidizing indices being 1313, 2036, and 955 at the respective pressures.

The data on McCloskey cores, Table 3, do not lend themselves to analysis on the above basis due to the distribution of permeabilities at the various pressures, but they support the contention that, in laboratory acidizing, higher indices result from treating low-permeability cores.

Any benefit from an analysis of the treating factors must be derived from the data on Niagaran dolomite, Table 1, as on the other cores the only factor in this index showing any irregularity is the time for treatment. On all cores it is to be noted that the time for treatment was approximately halved when the total pressure was either 1250 or 2500 lb. per sq. in.

TABLE 2

Acid treatment of Bedford limestone cores

No.	Pressure, lb. per sq. in., gauge		Time, min.	Acid volume, cc.	ΔN	Weight loss		Permeability, millidarcys			Acidizing index	Treating factor
	Upstream	Downstream				Grams	Percent	Before	After	Percent increase		
1	100	0	1.00	7	2.0	0.353	1.15	69	438	535	466	1.69
2	100	0	0.33	15	2.0	1.020	2.99	70	4600	6,470	2,160	10.70
3	100	0	0.30	12	1.7	0.814	2.12	19	3400	17,800	8,300	35.10
4	100	0	0.50	12	1.6	0.768	2.18	4.8	1750	36,350	16,695	83.3
5	Average		0.53	11.5	1.8	0.739	2.11	40.7	2547	15,290	6,905	32.70
6	1300	1200	0.25	12	1.6	0.718	2.04	51.3	2700	5,160	2,530	15.60
7	1310	1210	0.25	13	.....	0.637	1.88	67.5	2025	2,900	1,542	12.85
8	1315	1215	0.20	14	1.3	0.756	2.12	29.7	2835	9,430	4,448	39.25
9	1390	1190	0.24	14	1.2	0.905	2.34	9.5	1890	20,000	8,550	52.60
10	1390	1190	0.28	11	1.4	0.586	1.68	12.0	1950	16,140	9,600	26.95
11	Average		0.24	13	1.4	0.720	2.01	34.0	2280	10,726	5,334	29.55
12	2500	2400	....	8.0	3.5	1.353	4.71	39	2850	7,210	1,530	.....
13	2600	2500	0.25	9.5	1.4	1.150	4.00	49	5600	11,350	2,838	12.9
14	2600	2500	0.22	9.5	1.8	1.896	6.70	83	6000	7,128	1,065	8.8
15	2600	2500	0.20	10.0	1.5	1.201	4.24	160	6100	3,708	875	5.18
16	2600	2500	0.17	10.0	1.6	1.199	4.46	66	2800	4,143	926	15.17
17	2600	2500	0.20	9.0	1.2	1.089	3.82	41	6200	15,030	3,940	18.3
18	Average		0.21	9.3	1.8	1.315	4.66	73	4925	8,095	1,862	10.1

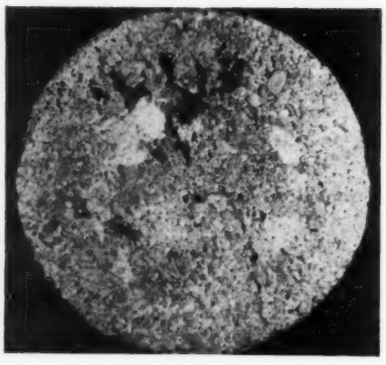

Fig. 7. Bedford oolitic limestone acidized at atmospheric pressure

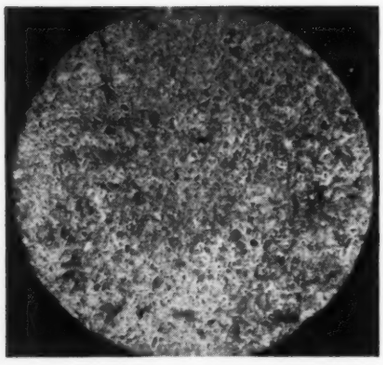

Fig. 8. McCloskey oolitic limestone acidized at 1250-lb. pressure

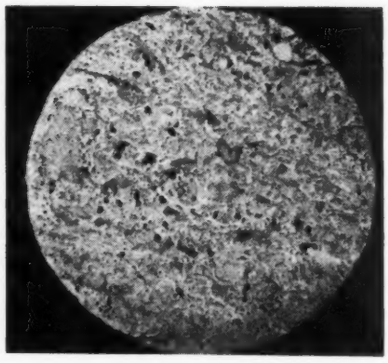

Fig. 9. McCloskey oolitic limestone acidized at atmospheric pressure

Moreover, the treatment time is more or less independent of either original permeability or differential pressure across the core. It is interesting to note, however, that on Bedford and McCloskey cores the treating factor is much higher than on the dolomite cores. Primarily, this is a consequence of the higher reaction rate.

The observed differences between atmospheric and high-pressure treatments appear to be mainly attributable to differences in the volume of undissolved carbon dioxide. In all treatments at high pressures, conditions were such that most of the CO_2 was dissolved (and that which was dissolved was compressed to small volume), whereas with atmospheric pressure on the downstream side of the cores the CO_2 formed by the reaction was present in the gaseous state. This condition resulted in Jamin action, which retarded the passage of the acid and slowed down the treatment, as evidenced by the longer times required to force the acid through the cores. The presence of undissolved gas also tended to cause the acid to channel through the larger pores, the small pores being blocked by Jamin action.

Figs. 4 to 9, inclusive, are photographs of the upstream ends of representative cores from the three formations after treatment. Fig. 4 is a Niagaran core treated at 1250 lb. per sq. in. and Fig. 5 is a similar core treated at atmospheric pressure. Figs. 6 and 7 show the same comparison on Bedford cores and Figs. 8 and 9 show McCloskey cores treated at high and low pressures, respectively. These pictures give perhaps the most striking and interesting evidence of gas blocking resulting in a tendency of the acid to channel.

Referring to Table 1, the average treating factor on Niagaran dolomite is increased approximately four times by treating under high pressure. Gas blocking at low pressure resulted in longer time being required to force the acid through the core. Inasmuch as these dolomite cores differ from the other rocks in their failure to treat to high permeability very quickly and easily, this effect was present throughout the treatment.

Another interesting feature of the data is the fact that on a given rock the acid consumption, as evidenced by normality change during treatment, was approximately the same irrespective of the pressure or time required for the treatment. It is well known that pressure retards the HCl-carbonate reaction and the fact that the acid was spent to about the same degree in a shorter time at higher pressure can be explained only by assuming it was reacting on more surface. This assumption fits in well with the theory of gas-blocking at low pressures, which would confine the acid to relatively few pores, whereas at the higher pressures better distribution of the acid throughout the interstices of the core would be expected.

Conclusion

Perhaps the most important single conclusion that can be derived from a study of the data obtained in this work is that there is less tendency for the acid to channel at high pressures than at low pressures. This phenomenon apparently is due to the fact that at low pressures more of the carbon dioxide evolved by the reaction is present as a gas; consequently, many of the pores are blocked by Jamin action, with the result that the acid channels through the larger pores. In comparing either the pictures of cores or the tabulated data, it should be remembered that the results obtained under high pressures probably more nearly approximate actual treating conditions because at the bottom of a well the acid is always under a pressure greater than atmospheric.

TABLE 3

Acid treatment of McCloskey limestone cores

No.	Pressure, lb. per sq. in., gauge		Time, min.	Acid volume, cc.	ΔN	Weight loss		Permeability, millidarcys			Acidizing index	Treating factor
	Upstream	Downstream				Grams	Percent	Before	After	Percent increase		
1	100	0	0.50	12	1.4	0.451	1.22	51	1300	2,450	2,006	7.84
2	100	0	0.42	12	1.8	0.910	2.51	70	2150	2,975	1,184	6.86
3	100	0	0.30	12	2.0	0.947	2.56	70	2700	3,757	1,468	9.53
4	100	0	1.08	12	1.3	0.438	1.14	36	1600	4,340	3,807	5.13
5	Average		0.58	12	1.6	0.678	1.86	57	1938	3,380	2,114	7.34
6	1315	1215	0.25	12	1.7	0.919	2.35	16	1600	9,900	4,215	50.0
7	1390	1190	0.50	12	1.0	0.592	1.58	4	2000	49,900	31,600	50.0
8	1390	1190	0.08	12	1.6	0.883	2.30	7	2300	32,700	14,250	178.6
9	1390	1190	0.20	14	1.7	1.092	2.82	6.7	2160	32,100	11,400	86.8
10	1390	1190	0.27	14	1.8	1.226	3.30	9.5	2700	28,300	8,600	46.0
11	1390	1190	0.17	7	1.8	0.834	2.22	50	970	1,840	830	7.0
12	1290	1190	0.23	8.5	1.3	0.576	1.48	42	1500	3,465	2,339	14.7
13	Average		0.24	11.4	1.6	0.875	2.29	19.3	1890	22,600	10,462	61.8
14	2600	2500	0.22	15	1.7	1.465	3.73	161	4100	2,450	657	7.06
15	2600	2500	0.20	13	1.6	1.217	3.18	190	4000	2,002	632	5.70
16	2600	2500	0.28	16	1.0	1.014	2.65	160	2800	1,650	622	5.95
17	Average		0.23	15	1.4	1.232	3.19	170	3633	2,034	637	6.24

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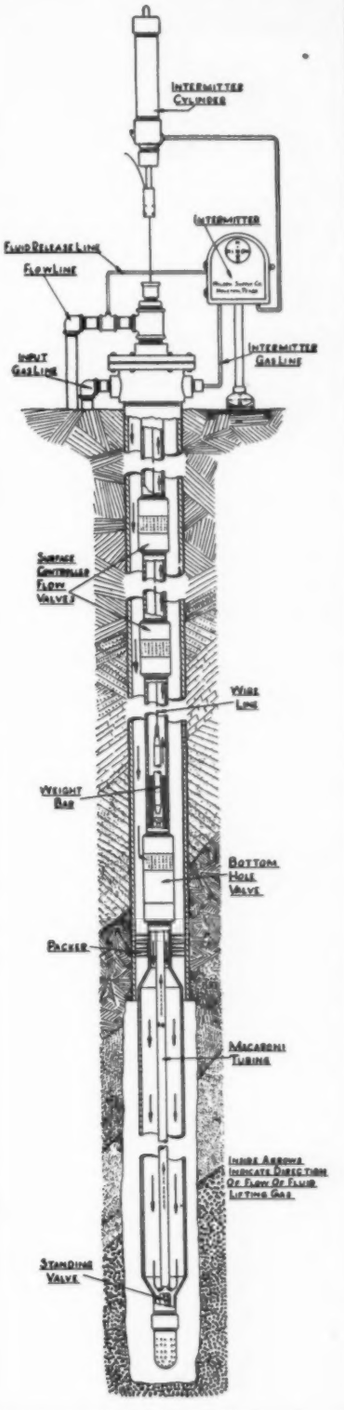

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Fig. 1. Worn tool joints on new drill pipe built-up on box end to restore elevator shoulder and to hard-surface tool joint

PETROLEUM ENGINEER Exclusive Feature

by

H. Lee Flood
Associate Editor

Hard-Facing Tool Joints As Practiced In Mid-Continent Area

☆ Field welding methods of applying hard-metal rods to worn tool joints have advanced rapidly during last several months

DURING the last year considerable progress has been made in the practice of rebuilding worn tool joints. Prior to that time, a great deal of thought and study had been devoted to the subject, thus laying the groundwork for the more intensive developments in recent months.

Even now there are many ideas being advanced as to the best way to rebuild a tool joint. One of the leading tool-joint manufacturers has rebuilt thousands of worn joints during the last 2 or 3 years by re-sleeving the entire joint, using sleeves or sheaths of metal of any degree of hardness desired. Several methods now in the formative stage may result in an economical method of hard-facing new tool joints. Presenting a greater diversity of ideas, however, are the methods, usually employed at the drilling rig or in local shops, whereby worn joints are rebuilt by welding various types of metal on the surface of the joint. Because of the widespread current interest in these field methods, the present article will be confined to a discussion of the variations in practice that have been developed. Although interest in the subject is widespread and considerable work has been done in California and other parts of the country, the developments in the Mid-Continent area are of especial interest.

Objectives of Hard-Surfacing

The application of hard metal to the surface of a tool joint to resist abrasion is only one of the factors in rebuilding a worn joint. It is usually desirable to regain the original gauge diameter of the joint, even to increase its effective diameter over part of or all the length of the joint, and nearly always it is essential to restore the square or tapered elevator shoulder to its original contour.

When the depth of the metal to be deposited exceeds $\frac{1}{8}$ to $\frac{3}{16}$ in., it is desirable to use a semi-hard metal. This is not so much to reduce the amount of the more expensive hard metal used but a composite metal build-up is tougher and less subject to cracking or shattering.

What Is Meant by Hard Metal?

Nearly everyone has some knowledge of the fields of application in which hard metal is used. In other industrial fields, hard metal has been used to tip dipper teeth on steam or mechanical shovels, plow shares, conveyors, and other points or areas subjected to severe abrasion. The relatively expensive use of diamonds in the first core drills was eliminated when hard metal became available.

Hard-metal welding rod in the form now available from leading manufacturers of this product is a hollow tube filled with granular tungsten carbide. The metal of which the tube is constructed will vary depending on the brand or the service for which the rod is intended. All rods are similar in that tungsten carbide is contained within. A general term that may be applied to this type of rod is "tungsten tube metal" rod.

Tungsten carbide itself does not melt readily. Consequently, the metal of the container tube serves as a binder for the tungsten carbide particles. Tungsten-filled rods designed for application with an acetylene torch are not coated. One type of tungsten-filled tube has the particles of tungsten carbide coated with flux, thus permitting it to be applied by the arc-welding method without spattering.

Other types of rods are available that possess a high quality of hardness but are definitely not to be confused with the hard metal rods containing tungsten carbide. These may be classed generally as self-hardening metals but there is one of this type that possesses an inherent hardness that remains unchanged, thus being neither self-hardening nor work-hardening.

Hard-Facing Methods

It is inevitable during the development stages of any new technique to witness several proposed methods for

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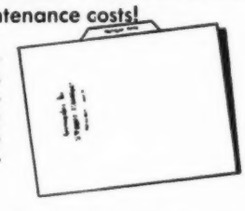
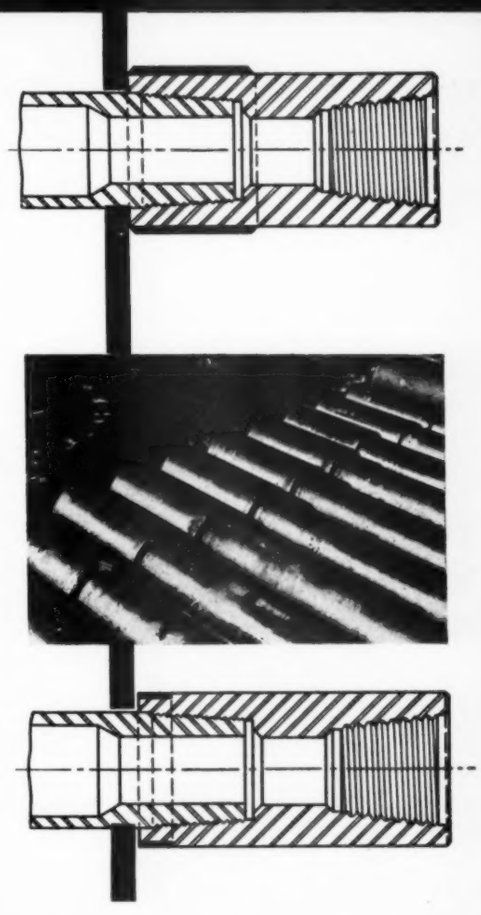
Electric Tube Borium or Coated Stoody Self-Hardening are the alloys used. They're applied either over the regular tool joint surface or inlaid into it—whichever method is preferred. Either way, this new Stoody application will make substantial savings for you in drilling and maintenance costs!

A special Stoody engineering bulletin—describing in detail the methods and metals employed—has been prepared. *Write for it.* It will give you the full story on how you get more life from your tool joints—at unusually low costs!



How tool joint boxes are hard-faced with Coated Stoody Self-Hardening only, an application widely adopted in Mid-Continent fields. No recess is machined into the joints—the hard-facing is applied directly to the surface of the collar to a thickness of from 1/8" to 3/16".

Elevator shoulders hard-faced on new boxes, an application which has proved highly successful in California. Joints are undercut 1/8" and heated to about 300° F. before hard-facing with either Electric Tube Borium or Coated Stoody Self-Hardening. Schematic drawing at right illustrates application in detail.



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STOODY COMPANY *Hard Facing Alloys*

accomplishing the same purpose. The rebuilding of tool joints has been no exception to this rule and thus it is that a variety of ideas have been advanced.

One method of rebuilding worn A.P.I. tool joints that has been used extensively and found to be satisfactory has involved the application of weld metal on the pipe end of the box half of the joint to rebuild the elevator shoulder and hard-surface the surface of the joint at the same time. The worn joint may be rebuilt on new or used drill pipe. In either case, the first step is to make-up the joint properly on the pipe so that the threads will be engaged correctly. The first welding operation is to put one bead around the pipe with a standard type of rod, welding the tool joint to the pipe. A copper clamp serving as a mold in forming the elevator shoulder is then placed around the pipe approximately ¾ in. from the end of the tool joint. The recess is then filled with a semi-hard rod until the built-up section is flush with the tool joint surface. To finish the job, approximately $\frac{3}{16}$ in. of hard metal is deposited over a total width of 3 to 4½ in. on the tool joint surface and the built-up section. In the Mid-Continent the metal is deposited so that it is higher than the surface of the joint. In California, operators prefer to machine a recess so the deposited metal does not exceed the diameter of the tool joint. In Fig. 1 are shown several tool joints that have been rebuilt in this way by one of the leading Mid-Continent drilling contractors. In this instance, worn tool joints have been built-up on new pipe. The amount of hard metal applied is limited to a band so that ample room on the joint is provided for the tongs. Inasmuch as the rebuilt shoulder is an important result of this operation, the box end rather than the pin end of the joint is the one built up and only rarely are both ends built-up.

Some newer types of tool joints that do not require threads to attach them to the drill pipe, either by being welded-on or forged at the time the drill pipe is made, have been rebuilt by depositing a band of hard metal at both sides of the upset (tong) surface and filling-in between them with a standard rod metal to provide a gripping surface for the tongs. On this type of joint, the pin end is built-up rather than the box end inasmuch as the heat might damage the female threads of the box. Fig. 2 shows a tool joint built-up in this way, made-up and ready to be lowered in the hole.

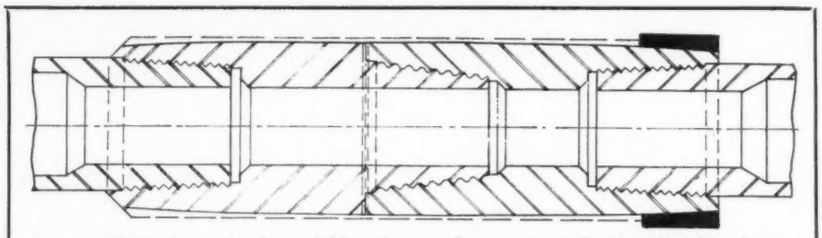

Fig. 3. Illustrating the barrel-like shape of a worn tool joint that has been rebuilt on the box end

Character of Wear

Some inexplicable actions have been observed as a result of hard-facing in certain ways. When the hard metal has been applied to elevator shoulders, particularly when the joint has been recessed, the surfaces of the joint adjacent to the hard metal will become worn so that a concave ring or groove is formed.

This action is not noted when the hard metal is applied without recessing and for this reason the so-called Mid-Continent method appears preferable.

Normally, a tool joint will wear at both ends, creating a convex or barrel-like surface. Fig. 3 is a sketch that shows this type of wear and also depicts the manner in which weld metal is applied to rebuild the joint. The deposited metal may be applied so that the elevator shoulder is reformed in its original position as shown or it may extend over on the pipe itself to form an entirely new shoulder.

Number of Rebuilt Joints

Information as to the number of tool joints that have been rebuilt is difficult to obtain. The total number would include, of course, all the tool joints being rebuilt in small shops by workmen who are not exercising proper precautions or employing proper materials.

In certain fields, tool joints are being rebuilt using ordinary mild steel rods and it is questionable whether the operator will get enough additional wear from the joints to return the cost of the work.

Aside from these makeshift attempts to rebuild tool joints, records are available indicating that several thousand tool joints have been rebuilt during the last year by reputable concerns using carefully supervised methods.

Should Joints Be Preheated?

When the weld metal is applied by the arc-welding method, it is highly important to preheat the joint to a minimum temperature of 300° F. This heat can be determined with sufficient accuracy in the field by established methods.

When the weld metal is applied with a welding torch, preheating is not necessary but it is important to heat the joint uniformly. Beads run circumferentially with successive beads begun on the opposite side from the one just finished will aid in uniform heat distribution.

Fig. 2. The pin end of the tool joint has been built-up with two bands of hard metal between which mild steel rod has been applied as a tong surface

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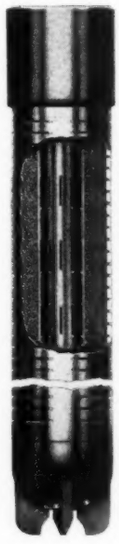

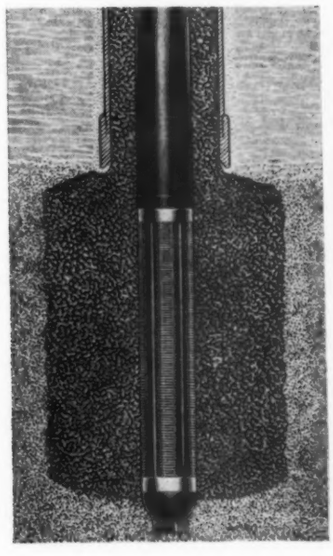

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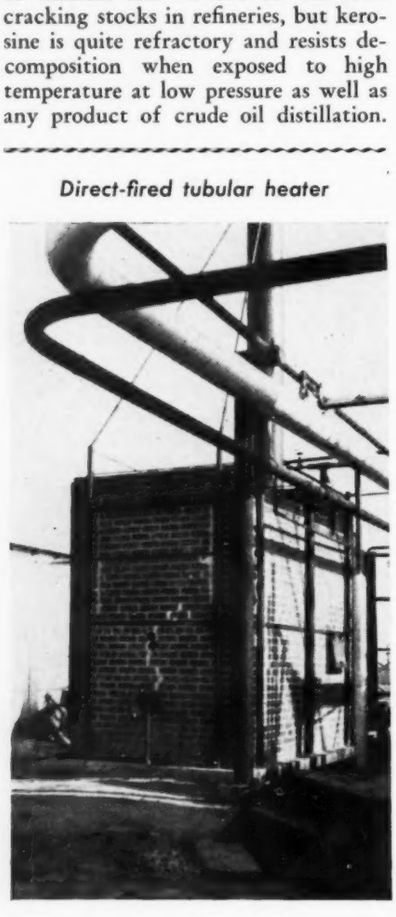
Compact Unit For Reconditioning Absorption Oil Employs Direct-Fired Heater

☆ Operated periodically as condition of absorption medium warrants, unit remains in service until entire volume of oil regains desired characteristics

J. C. Albright

AS THE type of absorption oil has been changed by many manufacturers during the last few years from a heavy, high-boiling mineral seal to one that may fall within the range of kerosine, and is frequently an export grade of water-white kerosine, reclaiming or reconditioning this material by distillation with direct-fired heaters to remove the heavy, tarry residuum has become quite practicable. When the former type of mineral-seal oil was overheated it usually meant that it would be cracked into lighter fractions, and much of the loss of absorption oil in plants employing direct-fired shell stills, or the modern pipe stills for that matter, was because of the mutability of this hydrocarbon fraction. Absorption oil—in the form of mineral seal—is one of the ideal cracking stocks in refineries, but kerosine is quite refractory and resists decomposition when exposed to high temperature at low pressure as well as any product of crude oil distillation.

Direct-fired tubular heater



Inasmuch as the efficiency of an absorption plant depends as much upon the quality of the absorption oil circulated through the system as it does upon the temperature of the oil and gas in the absorber, the quality of the oil stream should be maintained by removing the gummy substances that are, in most cases, the direct cause of emulsions and fouled bubble plates. These gummy substances may frequently, but not always, be traced to the field and to defective level controllers on the oil and gas separators permitting a portion of the crude to carry over into the plant gathering system. Adequate scrubbing facilities prevent slugs of liquid from entering the absorber, but, regardless of the efficiency of the demisting apparatus, entrained oil will eventually degrade the absorption stream.

Different types of absorption-oil reclaiming units are used in modern gasoline plants, ranging from small, steam-heated columns (some of which are equipped with vacuum apparatus) to elaborate systems equipped with tube stills as durable and efficient as in a modern cracking furnace. In most plants where the practice of reclaiming absorption oil is followed, the feed to the reconditioning unit is obtained directly from the denuded stream at the still outlet before it enters the heat exchangers so that the oil will enter the reclaiming unit at a relatively high temperature. Although most of these units are automatic in operation, a few are on hand control; neither method of control requires much attention by the operators after the system is balanced and in routine operation.

Description of Unit

One type of direct-fired absorption-oil reconditioning unit that operates at a higher temperature than the end-point of the material is used by the Wilmington Gasoline Company on Terminal Island at Wilmington, California. This unit has four principal parts: (1) the retort, or tubular heater; (2) a flash column employing process steam; (3) a valveless recirculating pump, and (4) a series of pipe condensers that empty into an accumulator. The retort is built of common red brick with a refractory lining in which is placed three banks of extra heavy seamless steel tubes so that the return bends are protected by the end walls of the furnace. Each bank of tubes contains seven tubes in a continuous coil above a large combustion chamber with tube hangers to prevent sagging.

The transfer line, carrying the heated oil from the retort, is connected to the upper part of the flash column, extending through the shell; the inside nipple is perforated to act as a spray directing the commodity downward. The steam used for processing the oil is introduced into the column at a point slightly below the normal fluid level through a perforated 2-in. pipe having the perforations in the upper side. An extended section of the flash chamber, smaller than the main shell, is placed at the top to act as a dephlegmator; vapors are released from

J. C. ALBRIGHT

was drilling superintendent for H. J. von Hagen in North Texas area, 1919-1921—With the Noble Oil and Gas Company, Burkburnett, Texas, from 1921 to 1923—Joined staff of the Dixie Gasoline Company in 1923 and became Texas manager—Employed by Phillips Petroleum Company in 1925 and was sent to New Mexico, where the company constructed a natural gasoline plant—Left Phillips in 1929 and for a time operated as a consulting engineer—For last 12 yeas has devoted virtually all his time to free-lance writing for trade journals.

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THE WIGGINS BALLOON . . . Available in capacities of 75,000 to 500,000 cu. ft., designed to act as a central gas holder in vapor saving systems serving groups of tanks through inter-connected, gas-tight piping. (The balloon shown above is connected to the vapor spaces of three 55,000-bbl. and two 18,000-gal. gasoline storage tanks.)

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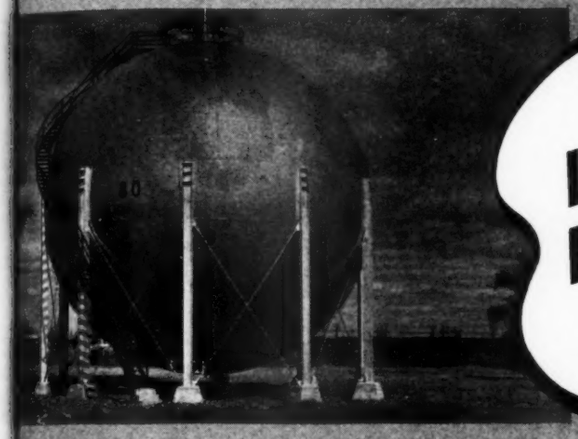

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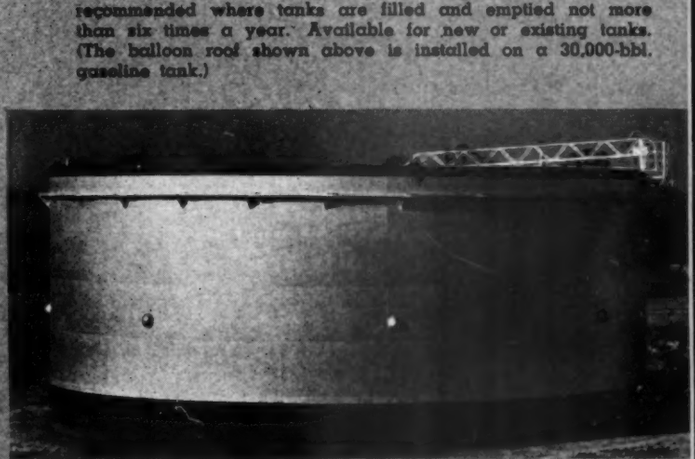
THE WIGGINS BALLOON ROOF . . . Used for all grades of oil that do not boil at atmospheric temperatures. Primarily recommended where tanks are filled and emptied not more than six times a year. Available for new or existing tanks. (The balloon roof shown above is installed on a 30,000-bbl. gasoline tank.)



THE WIGGINS BREATHER ROOF . . . Recommended for use on new or existing tanks 60 ft. in diam. or larger that are kept full or nearly full most of the time. This includes standing storage tanks for all grades of oil that do not boil at atmospheric temperatures. (The breather roof shown above is installed on an 80,000-bbl. gasoline tank.)

THE WIGGINS PONTOON ROOF . . . Primarily recommended for working tanks that are filled and emptied more than six times a year. Available for new or existing tanks. Also for blending tanks handling any grade of gasoline that does not boil at atmospheric pressure. (The unit shown above is installed on a 55,000-bbl. tank in pipe line service.)

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the distilled oil at the top through a combination vapor-outlet and safety-valve connection.

The vapors flow from the outlet of the dephlegmator section of the flash chamber to a series of 2-in. pipe coils placed in the water-cooling tower where the liquid runs to an accumulator tank having a water leg on the side to separate the water. This accumulator is connected directly to the lean oil surge tank so that the reconditioned oil can be bled into the system as desired or pumped to reserve storage.

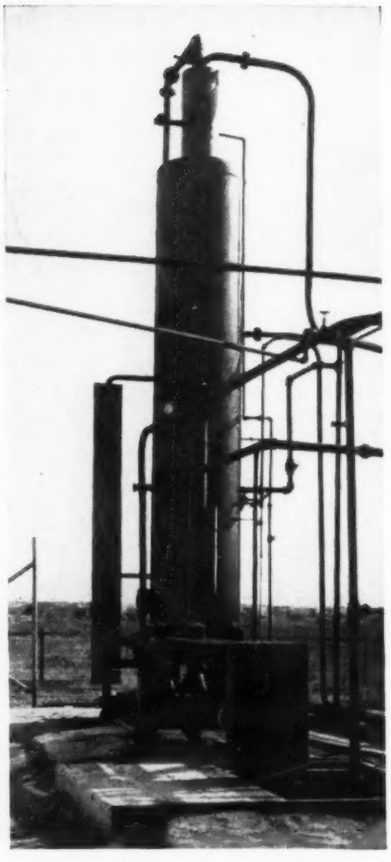
The pump is a duplex reciprocating steam-driven unit with the fluid chamber cover removed and the valves and springs eliminated. A pair of branched 3-in. pipes, attached to an adaptor plate forming part of a rectangular case enclosing the piping, are provided, for circulation of water to maintain a low temperature at the fluid end. The single 3-in. line connecting each pair of branched fittings is attached to a long suction-discharge run of 3-in. pipe, cased with 5-in. pipe as a water jacket. About 6 ft. from the pump, the combination setting of check valves is installed; these valves replace the valves normally used in the fluid end of the pump. The suction line to the pump is attached in pairs to a "boot-leg" or side section at the flash column, and is equipped with a double run, each fitted with a 2-in. Navy check valve; the latter valves function as suction valves. Between these valves and the pump, the discharge lines branch off, fitted with 2-in. steel check valves constructed as unions.

The pump chamber, branching lines, and suction piping are flooded with oil and cooled between the check valves and the pump body, but the circulated oil does not pass through the fluid end of the pump. The surge through the fluid end and through the 3-in. pipe runs serves as the connecting link to produce suction and discharge without permitting the hot oil to flow through the pump, as it normally would if the extra connections were not used and the valves were in place in the fluid chamber.

Type of Absorption Oil

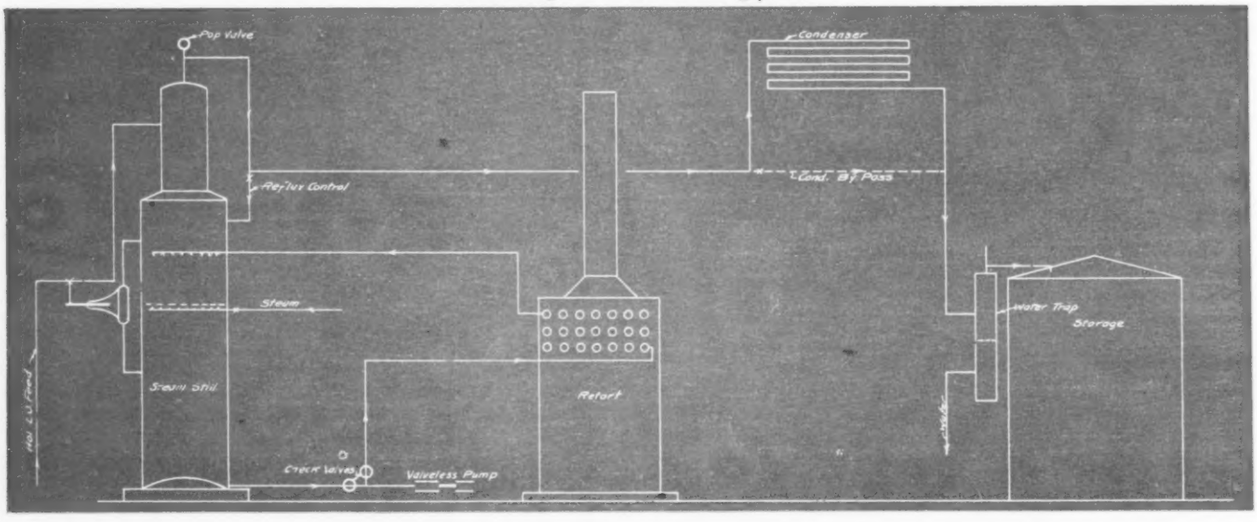
The type of absorption oil used in this gasoline plant is a kerosine distillate, having an A.P.I. gravity of 38.7°, and a boiling range of only 94°F. The initial boiling point of this material is 360°F., and the end point 456°F. It is fed from the gasoline plant still outlet at a rate of about 10 gal. per min. to the top of the flash chamber, and the bottoms are recirculated through the retort at a rate of about 60 gal. per min. The temperature of the oil passing from the heater tubes is maintained constantly at 500°F. with a thermostat-controlled fuel regulator that contains a micrometer adjustment between the helical actuating coil chamber so that the retort outlet temperature can be adjusted to any heat desired for adequate distillation. Once adjusted, the controller maintains a constant temperature on the oil regardless of the quantity circulated.

The oil in this plant is reconditioned as often as necessary, the need being determined both by visual inspection of the color, and by a laboratory analysis to determine the amount of contaminating gums. When the unit is put in service and balanced, it is usually operated for a period of from 20 to 30 days, depending upon the condition of the oil, but is shut down only after the entire amount of absorption oil has been clarified and reduced to its original distillation range. The small quantity of residual matter in the oil remains in the base of the flash column, and after the oil has been cleared up, this heavy oil is spread on plant roads.

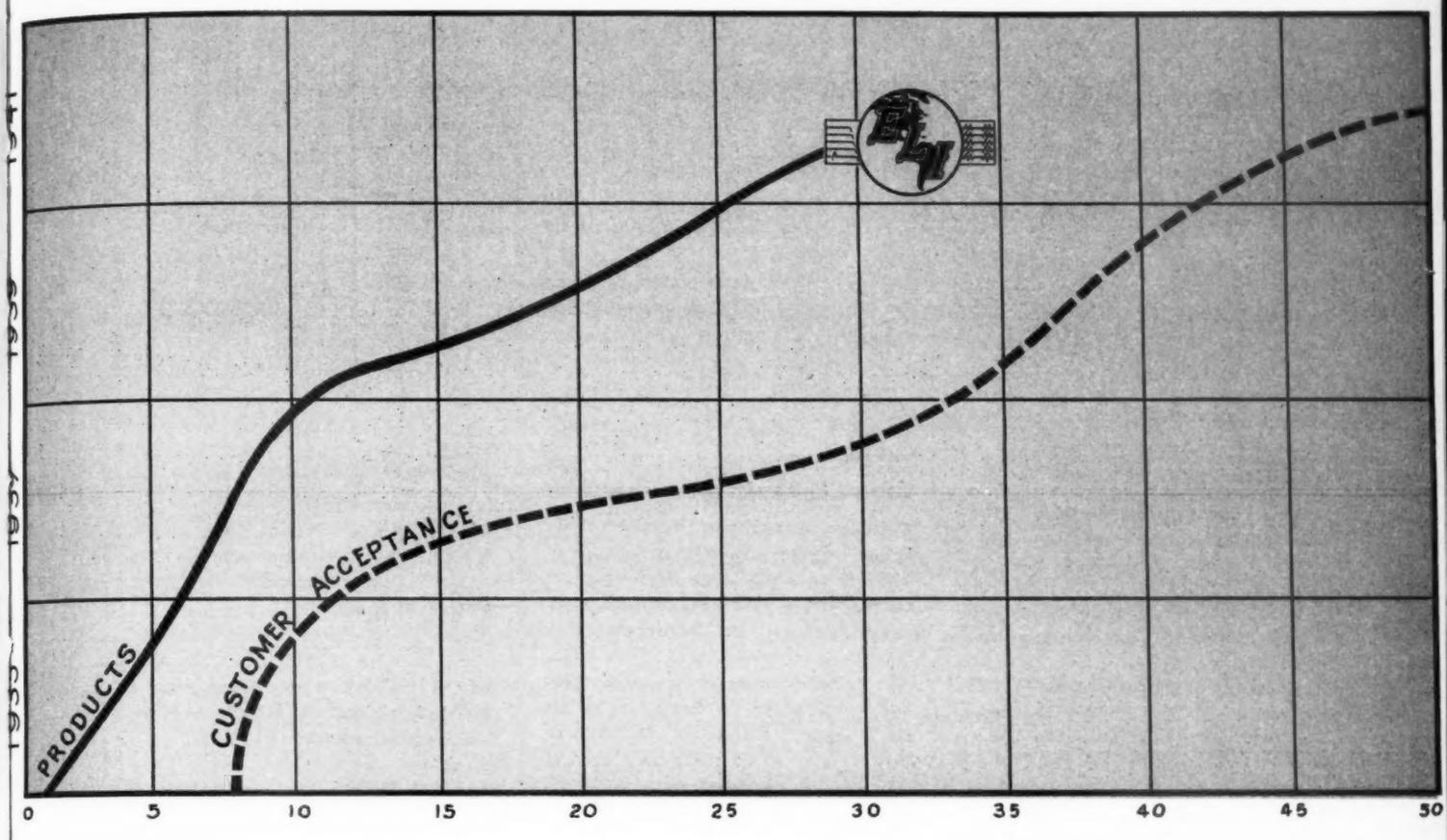


Flash column with pump suction chamber

Flow diagram of oil-cleaning plant



Achievement is the measure of Progress



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Well Completion Methods

CHARLES H. RANKIN

attended Colorado School of Mines, beginning in 1926—Employed by Geological Department of Continental Oil Company, 1929-35 — Production foreman of Jesse area, 1936—Superintendent of Shiprock District, Shiprock, New Mexico, 1937-39—In 1940 became production superintendent of the Colorado District, Rocky Mountain Division of the Drilling and Production Department of Continental, the position he now holds.

☆ New Mexico operation illustrative of results obtainable by use of recent improvements in technique

by Charles H. Rankin

Superintendent, Colorado District,
Continental Oil Company

AN EXCELLENT example of the results to be expected from the use of recent improvements in well drilling and completion techniques is illustrated in a well recently completed by a major company in New Mexico. This well was drilled as an exploratory well in a new field and full use was made of all modern improvements. Cores were taken with a wire-line core barrel during drilling at every point where indications of porosity or of saturation were found in the cuttings. Drill-stem tests were made when the cores supported the favorable indications. At the completion of drilling, an electrical survey was made and mud samples taken while drilling was in progress were submitted to conductivity tests (Fig. 1).

Casing was set and cemented through the entire productive series and then perforated with a gun-perforator at all points where either the coring, testing or electrical surveys showed indications of a favorable nature. In all, nine separate zones were tested without recourse to the use of liners or auxiliary strings of casing. Interpretation of the electrical log was handicapped to a certain extent because electrical surveys of other wells in the region that might have been used for comparative purposes were not available.

Coring and Testing

Coring established the top of the Pennsylvanian formation at a depth of 5697 ft. and was again used when the cutting from 6487 ft. showed saturated dolomite. At this depth a core was taken from 6487 to 6509 ft. This core showed saturated dolomite from 6487 to 6501 ft. A tester was set on the shoulder at 6487 ft. and showed only ½ joint of oil cut mud (Fig. 2). Drilling was resumed and at 6720 ft. coring was in progress when porous lime was found at 6724-30 ft. A drill-stem test made on the shoulder at 6710 ft. showed 335 ft. of oil and about 1,500,000 cu. ft. of gas in a 20-min. test.

Drilling was resumed to a total depth of 7507 ft. As all the producing formations had been drilled, it was decided to set casing on bottom and test all possibly productive formations by perforating with a gun-perforator.

An electrical survey was run before casing was set and showed indications of porosity at 11 different zones: 6440-55, 6470-6505, 6540-75, 6615-35, 6665-85, 6715-30, 6770-90, 6810-30, 7090-7130, 7145-80, and salt water at 7175-7200 ft. The casing was cemented at 7407 ft. with 313 sacks and although the bottom-hole temperature was greater than 150° F. no trouble was experienced in placing the cement.

Testing

In order to establish a definite horizon for measurement, the cement was washed and drilled-out to the float collar, found at a corrected depth of 7350 ft.

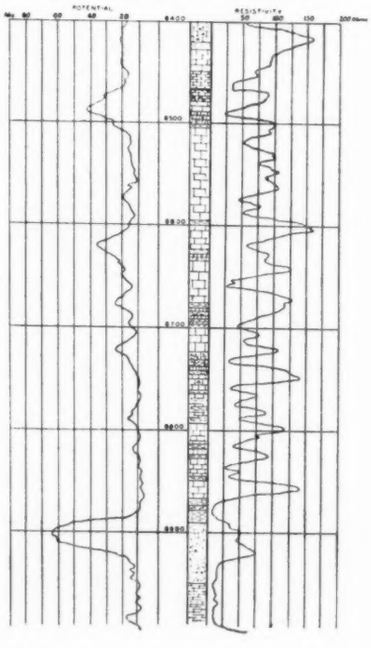
Perforations were then made with a gun-perforator from 7148 to 7160 ft. The well began flowing salt water almost as soon as the gun had been removed and it was necessary to kill this flow by pumping heavy mud into the hole. A cement retainer was set at 7136 ft. and 15 sacks of cement were squeezed into the perforations at a pressure of 3500 lb.

The casing was then perforated from 7113 to 7125 ft., but the well showed no kick when tested with a tester using a hook-wall packer. A cement retainer was set at 7097 ft.

Ten holes were made between 6810 and 6830 ft. and they tested dry. A retainer was set at 6748 ft. and the holes cemented with 4 sacks, squeezed at a pressure of 3500 lb.

Ten holes between 6740 and 6747

Fig. 1. Electrical survey made from 6400 to 7000 ft. with sample log added to show formations



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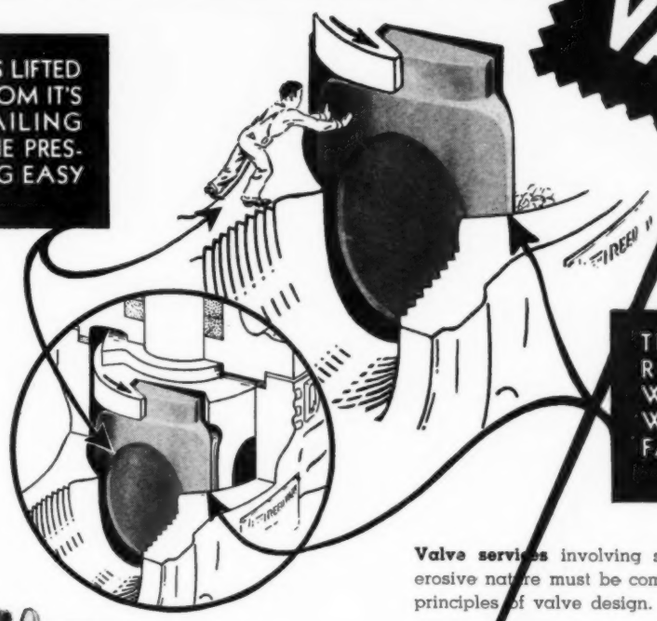

THIS EDGE OF THE DISC REMAINS IN CONTACT WITH THE INNER BODY WALL, WIPING THE SURFACE WHEN THE VALVE IS BEING OPENED.

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REED VALVES have exclusive features embodied in the design which assure clean seats of corrosion-resistant materials, positive closure, and easy, trouble-free operation.

Ease of operation is accomplished by the lifting action of the seating disc before the disc starts to move to the open position. A slight movement of the valve stem toward the open position lifts the seating disc directly away from its seat, partially equalizing the pressure on both sides of the downstream disc and reducing friction to a minimum. The valve is then moved to the open position with exceptional ease.

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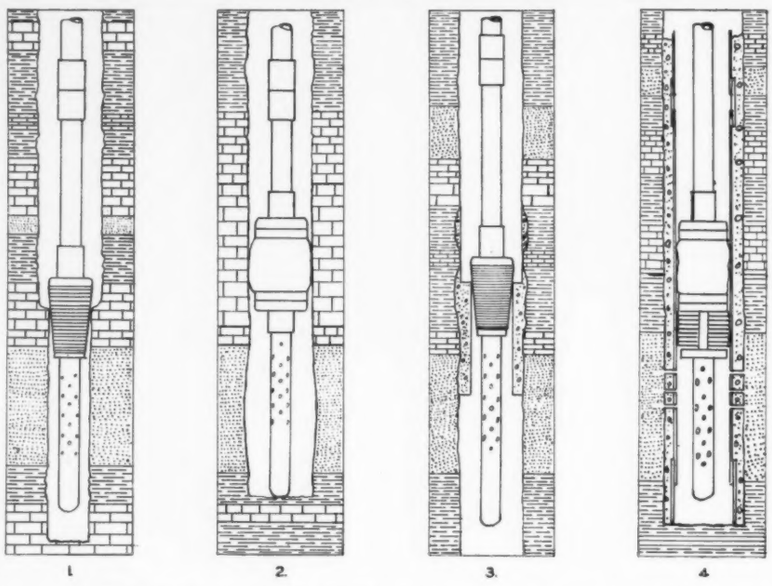


Fig. 2. (1) Rat-hole tester set on shoulder of cored hole. (2) Wall packer set in open hole. (3) Rat-hole tester set on shoulder made by drilling-out bridge plug. (4) Hook wall packer set in casing above perforations

ft. tested dry and a retainer was set at 6736 ft. A pressure of 3500 lb. was required to make the hole take fluid.

Perforations from 6710 to 6733 ft. showed a little salt water; these holes were squeezed-off with 20 sacks through a retainer set at 6677 ft. under 3500-lb. pressure.

Twenty holes at 6665-77 ft. tested, no show.

Twenty holes at 6615-35 ft. tested, no show.

Twenty holes at 6470 to 6503 ft. tested with a hook-wall packer showed a little oil- and gas-cut mud and a small amount of gas.

All retainers were then drilled-out to 6736 ft. and perforations were made from 6724 to 6730 ft. These perforations tested dry but would take fluid at around 2000-lb. pressure. One thousand gallons of acid was pumped in at an initial pressure of 2000 lb. and a final pressure of 10-in. vacuum. Tubing was run and set with a packer and this horizon tested more than 100 bbl. per day with 1,500,000 cu. ft. of gas.

Operations were suspended at this point but the well is now in a position to produce from either the lower zone (6724-30) or the upper dolomite zone (6480-6500) by the use of a newly developed retainer production packer, permitting either zone to be produced at will or enabling both to be pumped together.

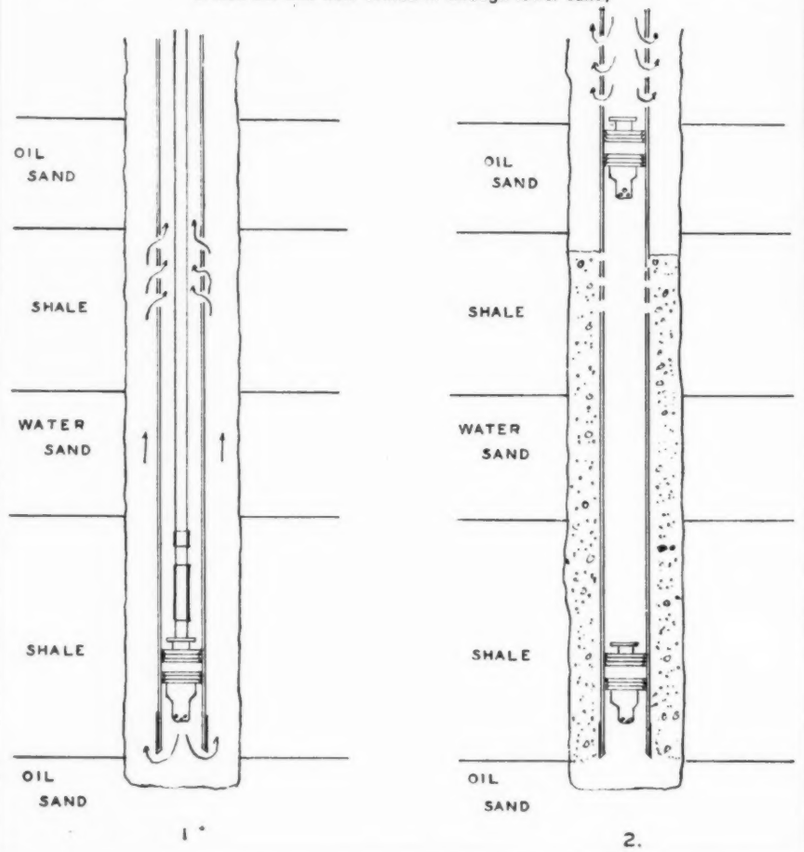
Thus is demonstrated the value of newer testing methods over those older methods of testing in which each show required a string of casing and upper zones that did not appear to have potentialities were cemented-off. By testing in the newly developed manner ten separate zones were tested individually and the potentialities of each fully explored.

Another example of a recent two-zone completion is shown in Fig. 3. By using squeeze cementing through a cement retainer and perforating in the producing zones a water horizon lying between them was effectively shut off. By the use of this method a venture that might have been only moderately profitable had large quantities of water been encountered was made commercially profitable.

Squeeze cementing, gun-perforating, zone testing, and the development of the devices that have made these methods practical have greatly increased the opportunities for the maximum utilization and development of new wells and the exploitation of undeveloped zones in older fields.

Fig. 3. (1) Cement retainer set in casing ready to cement water sand. (2) Water sand cemented, retainer set as bridge plug, hole ready to cement through perforations above upper pay zone

(Well will be completed by perforating opposite upper sand for testing; lower retainer will be drilled-out and hole drilled-in through lower sand)



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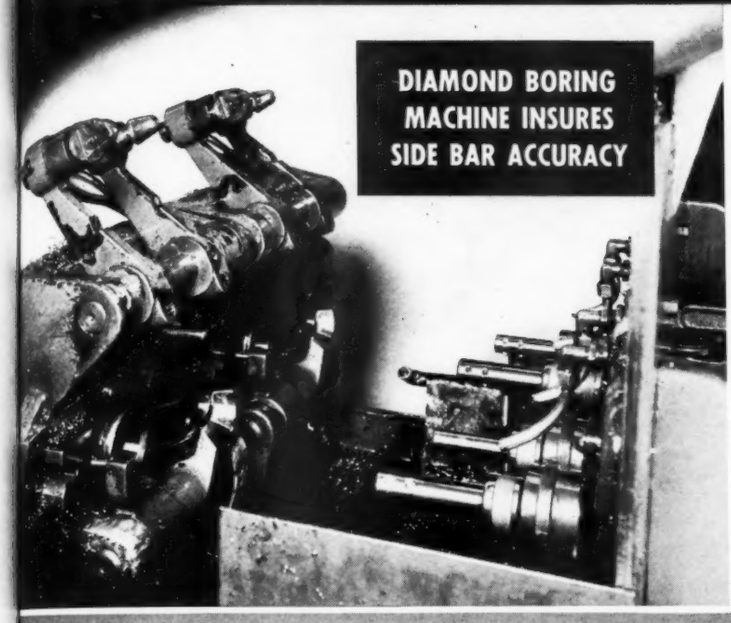

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IN ROTARY CHAIN, as in everything else, accuracy means economy. That is one of the reasons why Ideal Rotary Chain gives such consistently long service. In addition to precise manufacturing methods and efficient utilization of lubricant, all parts subject to wear are made from wear-resistant alloy steel, heat treated to obtain the best combination of toughness, strength and wear resistance.

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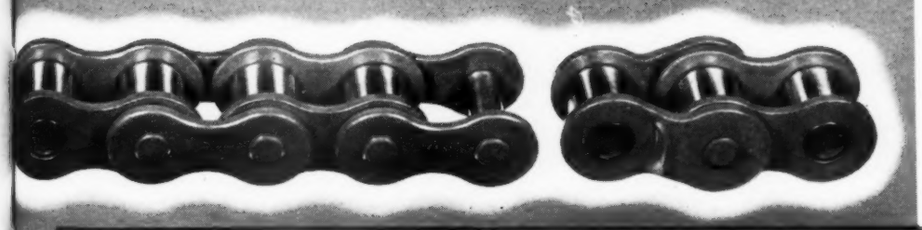

IDEAL ROTARY CHAIN is made in four types, which include seven distinct specifications as shown in the Brief Specifications below.

	TYPE G		TYPE F		ASA No. 200	No. 3⅛	
	No. 3 API	No. 4 API	No. 3 API	No. 4 API	Roller Single	Single	Double
Pitch in Inches	3.075	4.063	3.075	4.063	2.500	3.125	3.125
Ultimate Strength in Lbs.	48,000	112,000	75,000	170,000	95,000	115,000	115,000
No. Links in Approx. 10 Feet	39	30	39	30	48	39	39
Weight, per Ft. in Lbs.	7.3	16.5	8.5	17.2	11.0	12.6	24.6

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Electrical Examination of Coatings On Buried Pipe Lines

PETROLEUM ENGINEER Exclusive Feature

☆ Details are given of test equipment and procedures for determining position of larger holes in coating

by J. M. Pearson

Physicist, Susquehanna Pipe Line Company

THE basic principles involved in present methods of locating holes in buried pipe coatings may be summarized as follows:

(1) An alternating current is passed from the pipe metal to the soil through the holes in the coating.

(2) The locations of the "electrical leaks" are determined with suitable indicating apparatus and marked for excavation.

By proper use of the apparatus in examination of the leakage current paths it is possible to deduce that the coating is generally good with a few scattered holes or to deduce that the coating has become generally conducting. In the latter case, it is then possible to determine the position of the larger holes through which considerably more than the average leakage current passes. It is usually easy to locate the end of a coated section by the same methods.

In the following discussion, the methods of applying these principles in the field will be explained and details of the apparatus and its operation will be given.

J. M. PEARSON

in 1929, left the California Institute of technology where he had a teaching fellowship, to undertake experimental work in electrical geophysics for the Sun Oil Company at Dallas, Texas—In 1931 was transferred to the Susquehanna Pipe Line Company as physicist and since has been doing electrical work in connection with corrosion and control equipment.

Current Flow—Pipe to Earth

For ordinary coatings the minimum practical requirements of the a-c. power source have been found to be between 0.005 and 0.010 amp. at 1000 cycles per second. This can be supplied by a microphone hummer* or similar apparatus. Under average conditions, between 1000 and 2000 ft. of coating can be tested on each side of the point of current application, the distance decreasing with poorer coatings and lower soil resistivities. If more power is used for excitation, the increased range is not proportional to the added power; as a matter of fact, in the operating range of the apparatus, sensitivity of the detector may be reduced by one half each time the power is quadrupled. Increased power is occasionally an advantage, however, when large amounts of stray current interfere with observations.

*Of the type manufactured by General Radio Company.

Fig. 1 is a diagram of the exciter set-up. The 1000-cycle source is connected between the pipe and a ground rod 100 ft. away. The ground need not be very elaborate, a resistance of no more than 200 ohms working quite well. The hummer is battery-driven and should be reasonably steady in output.

All current circulated between the pipe and ground rod must return to the pipe from the earth in only two ways:

(1) Through the holes in the coating.

(2) As charging current via the electrical capacity between pipe and ground through the good part of the coating.

How the current splits up will, of course, depend on the efficiency of the coating as an insulator. At 1000 cycles or less, the conductivity of soil water penetrating a very small hole in the coating will carry as much current as many square feet of good coating that is only $\frac{3}{16}$-in. thick. The result is a concentration of current flow toward the holes, and their location is revealed by increased voltage drop in the soil due to this concentration. Fig. 2 is a diagrammatic representation of this condition.

The concentration of current at the holes produces the same voltage peaks in the earth no matter which side of the pipe is exposed in the failure. This fact is made use of in the method of detection, which depends on measuring the voltage drop in the earth only, no pipe contact being used.

The better the general condition of a coating, the more relative disturbance is produced by a small leak. This turns out to be an advantage as in a good coating the isolated failures are likely to be small and it is essential that the method of locating the holidays aboveground be quite exact in order to find them on excavation. Poorer coatings that have failed generally immediately reveal themselves as such, and under these conditions it is possible to locate the larger holes. Usually, in this case, inspection of the coating at almost all points will reveal holes. The only failures of interest, of course, are the exceptionally bad ones.

Detection of Holes

In order to detect the holes in the coating it is necessary to locate those points on the ground above the pipe where the leakage current has disturbed the earth-potential. This may be accomplished by two men, one of whom carries the amplifier and indicating meter, the other man providing a reference ground connection. Each man has steel cleats on his shoes. The cleats of the first man are connected to the amplifier shielding; the second man's cleats are connected to the amplifier input. The arrangement is illustrated in Fig. 3.

The man designated as "B" listens to the amplified output and watches the output meter. This is necessary because of the various extraneous noises

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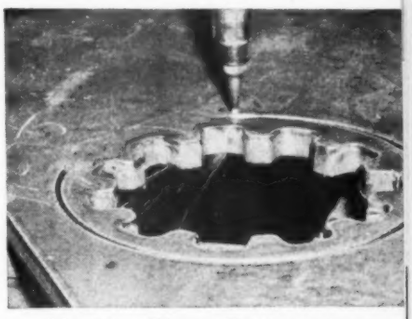
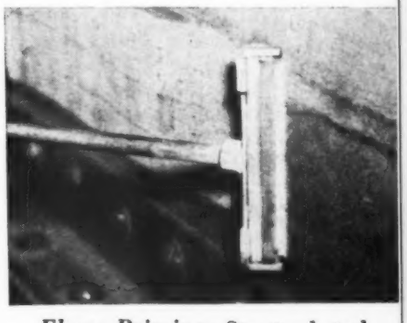
The oxy-acetylene process provides good "insurance" against costly delays in oil field operations and undue depreciation of equipment. If you are equipped to use this versatile process you will find that the moderate cost of your oxy-acetylene apparatus usually will be repaid many times over through savings in time and materials. A few typical applications of the oxy-acetylene flame are shown here.

Welding – Practically any metal part that breaks or wears can be quickly restored to usefulness by oxy-acetylene welding. Welding makes pipe joints permanently leak-proof. It is used, too, to hard-face surfaces with Haynes Stellite rod.

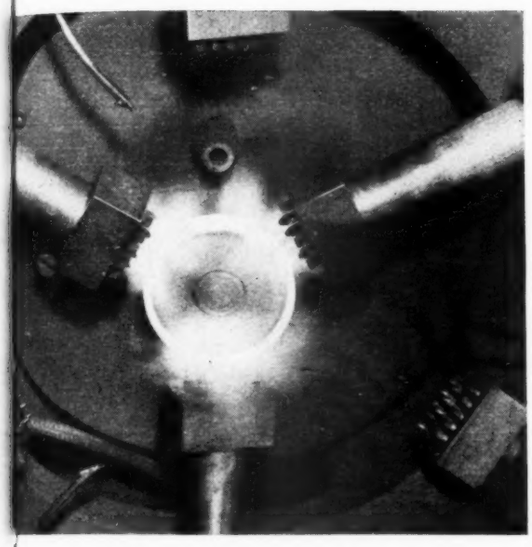
Hand-Cutting – The hand-cutting blowpipe is useful for beveling or reclaiming pipe, for the production of small steel parts, for cutting steel or pipe to length, and for altering machinery and equipment.



Machine Flame-Cutting – When new parts are needed, oxy-acetylene flame-cutting machines—portable or stationary—quickly produce the desired shapes from stock steel, ready for fabrication by welding.



Flame-Priming – Structural steel and tanks can be prepared for long-lasting paint jobs by means of oxy-acetylene flame-priming. This process removes loose scale, rust, and surface moisture, leaving a warm, dry, clean surface on which paint flows freely and bonds tightly.



Flame-Hardening

Oxy-acetylene flame-hardening imparts a hard case to wearing parts to make them last longer. This is done by heating the area to be hardened with oxy-acetylene flames, and then quenching with water or oil. Commonly used steels and high tensile cast iron can be flame-hardened successfully. The picture at the left shows a gear being hardened by the "spinning" method.

Advantages of Flame-Hardening

In many cases, oxy-acetylene flame-hardening is the only practical method of hardening wearing parts. Some of the advantages of this process are:

1. Parts of any size or shape can be flame-hardened.
2. There is no appreciable distortion.
3. The toughness of the core is unaffected.
4. Chemical composition of the metal is unchanged.
5. Penetration can be closely controlled.
6. The hardened area does not spall off.
7. Flame-hardening equipment requires only a moderate investment.

Typical Flame-Hardening Applications

Many parts used in oil field operations are today being flame-hardened, both by manufacturers of equipment and by users in the field. Some typical examples are:

Gears	Sprockets	Shafts
Pump Plungers	Piston Rods	Brake Drums
Wash Pipes	Pump Liners	Tool Joints
Pump Cross Heads	Cams	Sheave Wheels

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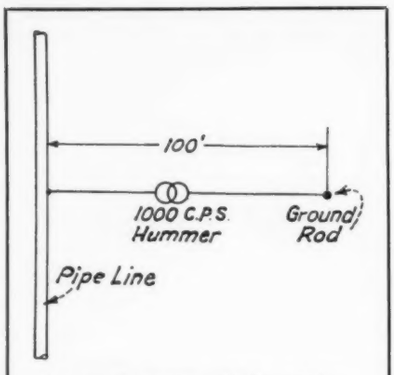


Fig. 1. Diagram of the exciter set-up

picked up. "B" must determine by ear if the kicks on the meter represent the 1000-cycle whistle or just incidental noises.

The two men walk along the line and as "A" approaches a hole in the coating, "B" will detect a strengthening tone and observe an increase in the meter reading. The reading will become a definite maximum when "A" is just over the hole. As they proceed, the maximum reading will recur when "B" is over the same spot. The exact location can be determined if both men stop walking while "B" moves forward and backward a few inches at a time to find the highest reading on his meter.

If a peak is observed when "A" is at a given spot, but does not recur when "B" reaches the same spot this is due to the presence of two holes (about 20 ft. apart, in this case). When this happens "A" should walk beside "B" with the wire at right angles to the line. This will introduce a weak tone due to the charging current flowing through the good part of the coating. The peaks are easily determined by "B" as sharp increases in this tone.

Test for Isolated Hole

This test is a check on the presence of only one failure in more than 40 ft. of pipe coating, a condition that is found on the better coatings, even on poorer coatings when only recently laid. To make the test, "B" stands over the hole at the point of maximum reading while "A" walks around him slowly. If "B" is over a single hole in a generally good coating the meter will read nearly the same over the entire circle. At right angles to the line, the charging current increases the reading slightly, but the single failure produces an almost symmetrical circular field of potential gradient.

Generally Poor Coating

To test generally poor coating, "B" stands over the line while "A" again walks in a circle. If the coating is generally poor the meter reading at right angles to the line will be high, and dip quite low as "A" walks over the trench. (If the line is bare the reading over the line will dip substantially to zero.)

In this case, the large number of failures in the coating produces a current flow that is substantially radial from the line, all the potential gradients appearing on the ground's surface at right angles to the line. A coating as poor as this usually will make it necessary for "A" to carry the wire at right angles to the line so "B" can pick up the worst failures.

Test for End of Coating

When "A" approaches the end of a section of good coating, walking as

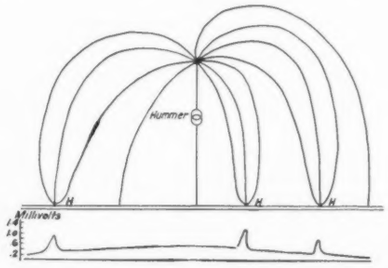


Fig. 2. Variation of soil potential due to charging and leakage currents. "H" is hole in coating

in Fig. 3, "B" will detect a rise in tone that reaches a peak that will be maintained at substantially the same value until "B" reaches the end of the coated section. At this time the reading will drop to zero when both men are over the pipe.

Line Location

In order to walk directly above the pipe it is usually desirable to mark the line location in advance so that both men can keep on line. This is conveniently done with a shielded induction pickup coil and the same amplifier.

With the hummer on, the coil is plugged-in and held flat, with one side parallel to the ground. If the coil is moved from side to side of the trench, a very definite minimum tone will be heard when the center of the coil is directly over the line. The line can thus be accurately located, and at the same time the distance at which the current becomes too weak can be approximately determined. It is usually convenient for "B" to carry the pickup coil and to locate the line as the inspection progresses.

Other Means of Excitation

When the observer knows that alternating current is flowing through the coating, it is unnecessary to use the hummer. This condition occurs in most cathodic protection installations that use unfiltered rectifiers (120-cycle ripple for single-phase, 180- or 360-cycle ripple for 3-phase, 60-cycle supply) or motor generators (commutator ripple).

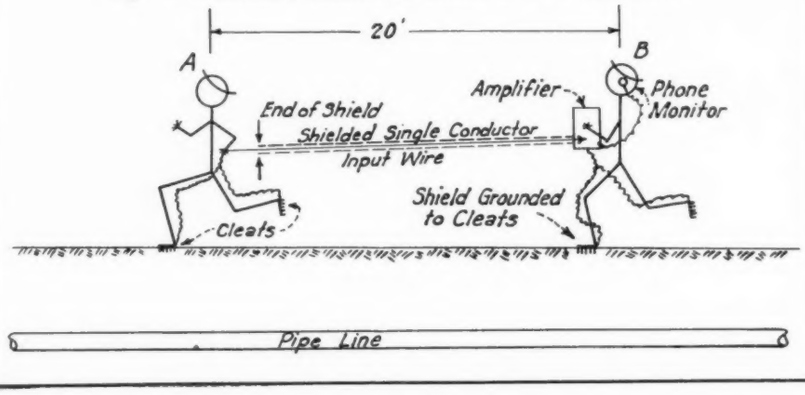
In some cases stray 60-cycle power current will be noted, but it is not trustworthy unless the observer knows it actually is flowing from pipe to ground.

Examination of Coating

After the line has been uncovered, the same hummer set-up can be used to find the actual failure. To do this, the amplifier is grounded to earth, and the coating explored with the free end of the input wire. It is usually possible to get a tone anywhere on the coating when doing this, but the tone increases sharply when the wire is put near the hole. An alternative method is to probe between earth and coating with an ordinary ohmmeter.

The holes found in a good coating may prove to be so small that they are determined with considerable difficulty on the excavated line. In many cases there is no break in the coating, the electrical leak being due to flow of the coating away from a point of high

Fig. 3. Illustrating relative positions of two operators



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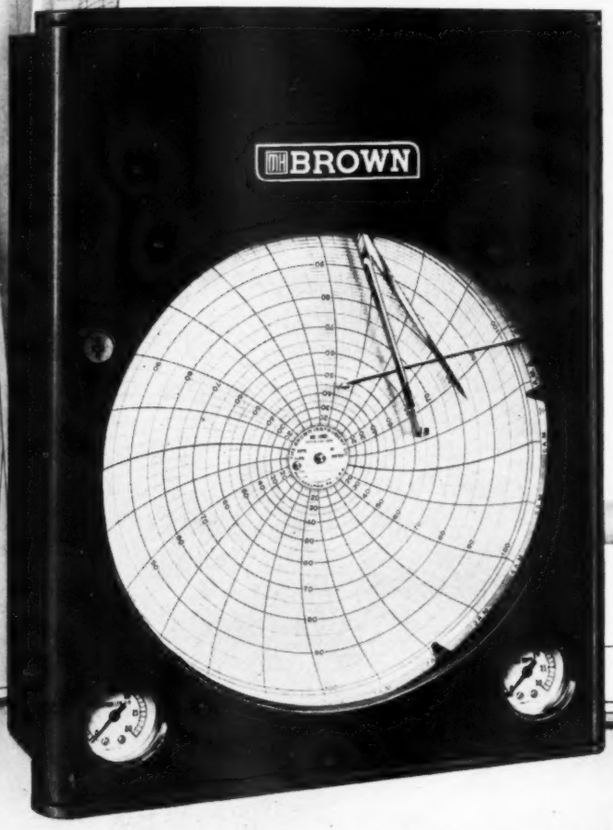

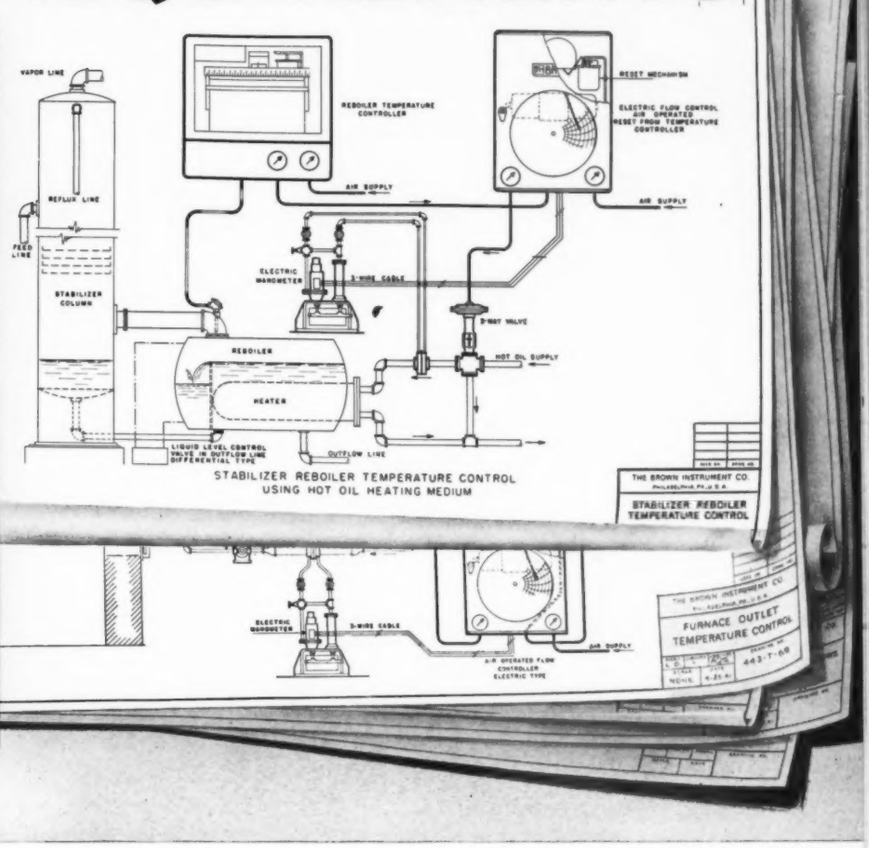

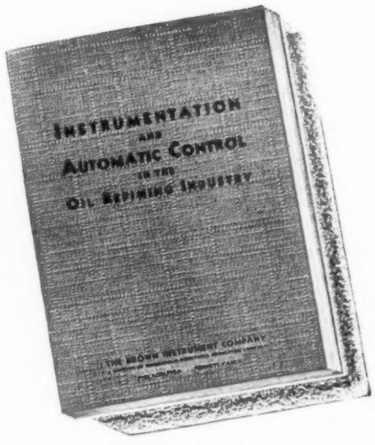

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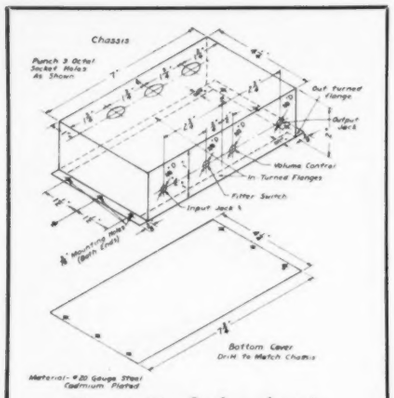


Fig. 4. Linefinder chassis

stress, allowing the wrapper to contact the line.

The pattern test developed by Scott and Ewing[1] is an excellent tool for finding small leaks.

In poorer coatings the failures are usually visible on inspection.

Apparatus

The amplifier used for this work should be portable and have a gain of 110-130 d.b. Figs. 4 and 5 show the chassis and the schematic wiring diagram. Fig. 6 shows one form of carrying case, made of fiber-covered plywood.

In assembling the amplifier, the output choke should be mounted above the output jack, and the 2.0 microfarad condenser (isolating filter) should be over the input. The output meter is mounted in the carrying case and connected across the output jack. A 1000 ohm-per-volt, 0 to 5.0-volt Weston Model 301 rectifier-type meter is most suitable. The meter wires should be shielded, and each tube must be individually shielded. Shielded grid wires are run upward through the chassis. All other parts mount on the socket terminals inside the chassis, the shielding being completed by the bottom plate. Brush crystal-type high-impedence telephones are recommended as they produce no magnetic field to interfere with the pickup coil.

The pickup coil frame and assembly are shown in Figs. 7 and 8, respectively. The winding consists of 20,000 turns of No. 40 enameled magnet wire, painted with National coil dope during winding. The winding is covered first with one layer of cellulose scotch tape, then a protective cushion of cotton string (chalkline) is wound on. Next the coil is shielded by tin foil, insulated and overlapped as shown.

The final covering of friction tape is applied and varnished. The copper handle serves to connect the operator to the shielding and to prevent feedback from his 'phones.

Measurement of Coating Conductivity

Local measurement of coating conductivity[2] is based on the making of suitable ground coupling measurements between the pipe and certain points on the surface of the ground. By use of the laws of radial current flow, taking into account the electrical image of the pipe in the ground surface, a simple set of measurements yields the coating resistivity in terms of the earth resistivity. Obviously such measurements should be made over uniformly good coating or over uniformly leaky coating so that current flow near the line will be radial. Poor results are to be expected over noticeably non-uniform coating.

Let b = depth of center line of pipe in ft. or in.

d = diameter of outside of pipe metal in same units as "b"

R_1 = coupling resistance between Stake 1 and pipe

R_2 = coupling resistance between Stake 2 and pipe

R_3 = coupling resistance between Stake 3 and pipe

K = coating leakage resistance in ohm-ft.

ρ = soil resistivity in ohm-ft.

Fig. 9 illustrates the relative positions of the stakes, etc.

K and ρ can equally well be in ohm-cm. or any other unit so long as both are expressed in same units. K is the resistance in ohms through one linear foot of pipe coating, so that the line diameter d must be considered in reducing results to ohms per sq. ft. leakage resistance.

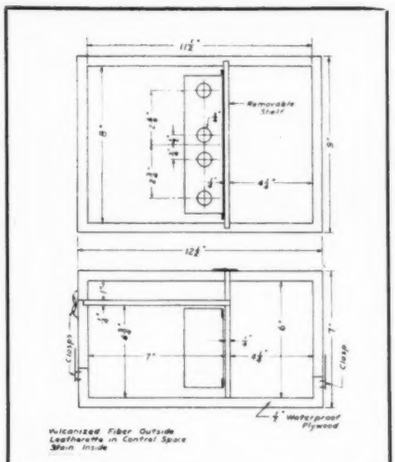


Fig. 6. Carrying case for linefinder and geophone amplifier

The method of taking the measurements is to connect a voltmeter across terminals (1) and interrupt I amperes at the anode. The *swing* of the voltmeter is recorded. This is repeated five to ten times to obtain a representative average value for the swing, which is the change in voltage. The swing in volts is then corrected for the resistance of the stake (No. 1) and connecting wires, and for instrument errors, to give the change of voltage $\triangle E_1$ in true volts under open-circuit conditions. Under very steady voltage conditions, potentiometer measurements can be used. As a voltage swing is used, iron ground stakes are usable because their potential (also the pipe potential) cancels out. The ratio $R_1 = \frac{\triangle E_1}{\triangle I}$ in ohms is the coupling resistance of the anode to the earth at Stake 1.

In the same way R_2 and R_3 are measured. It is unnecessary to interrupt the anode current entirely, using instead a swing of current measured as $\triangle I$ amp. Of course, enough current swing should be used to make the $\triangle E$ readings reasonably accurate. In each instance, the voltage swing between pipe metal and a point in the earth is determined. Thus each measurement includes IR drops in coating and earth.

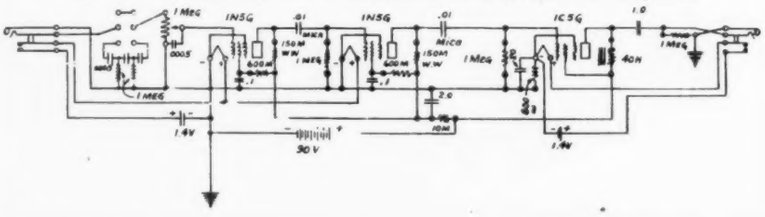
The stakes S_2 and S_3 are spaced on both sides of the line at a distance of three times b, the depth of the pipe. This spacing simplifies the formula and permits the use of logarithms to the base 10.

Then: $$K = 0.367\rho\left(\frac{2R_1}{R_2+R_3-2R_1} - \log_{10}\frac{b}{d}\right) \text{ohm-ft.}$$

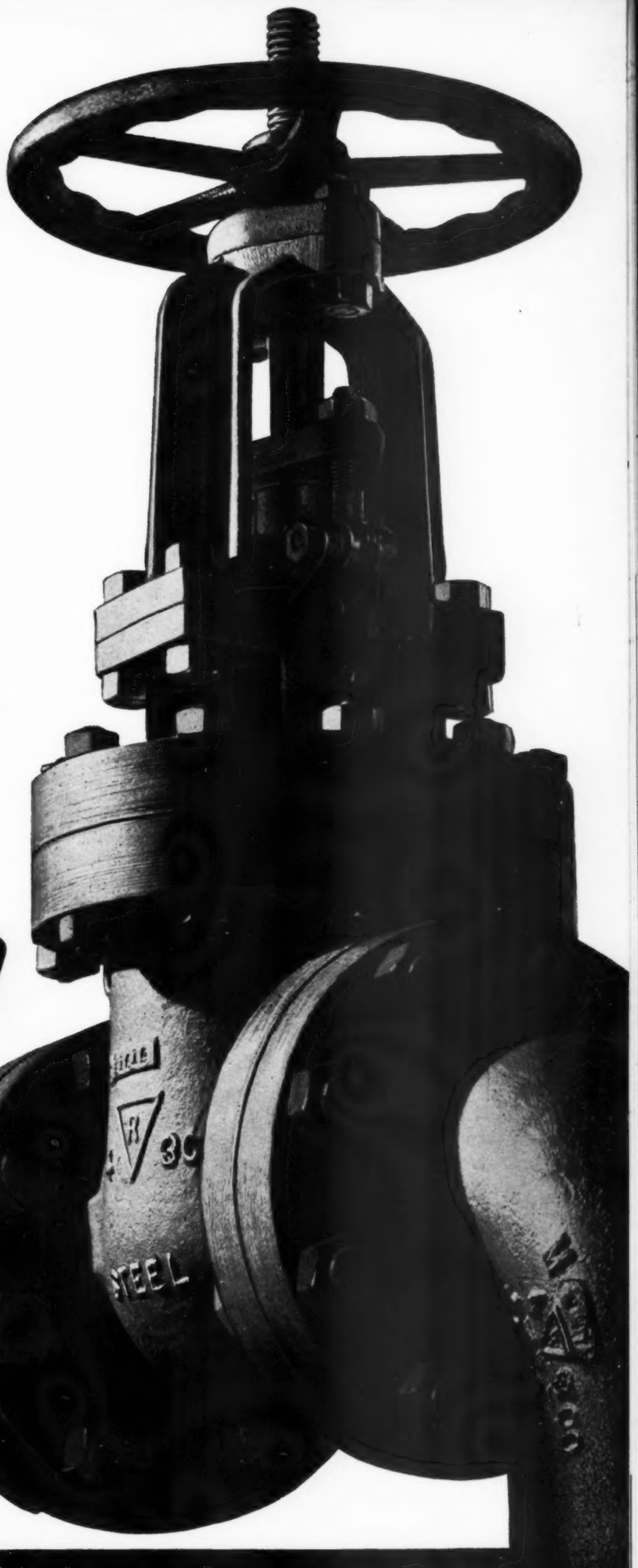
[1] "Electrolytic Method for Determining Condition of Non-Metallic Pipe Coatings," by Scott Ewing and Gordon N. Scott, *A.G.A. Monthly*, Vol. 16, No. 14, pp. 136-139, April, 1934.

[2] Dr. Gordon N. Scott's paper, "A Rational Approach to Problems in Cathodic Protection," *The Petroleum Engineer*, May and June, 1941, carries a much more detailed analysis of this method, with examples from field practice.

Fig. 5. Wiring diagram of linefinder and geophone amplifier



GUTS!



One look tells you that this 300 lb. Cast Steel Gate has the **guts** you've got to have in valves today.

For strength and rigidity, stout body and bonnet flanges. To stand up against corrosion and erosion, thicker wall sections.

A rugged stem to wedge connection to end another cause of maintenance.

To prevent jamming; the exact machining of more than ample wedge guides cast integral with the body.

To hold maintenance low, a heavy wedge that resists distortion. For long service at top temperature and pressure ratings, facings and seats of Stainless Steel, heat treated to prevent galling.

That's the story of this Gate Valve. You can depend on it for service to 300 lbs. at 750° F.—300 lbs. at 900° F. with Alloy Steel—just as definitely as you can depend on every READING-PRATT & CADY oil industry valve to do the job for which we recommend it.

READING CAST STEEL VALVES AND FITTINGS
PRATT & CADY BRASS AND IRON VALVES
D'ESTE VALVE AND ENGINEERING SPECIALTIES

A Division of **AMERICAN CHAIN & CABLE COMPANY, INC.**

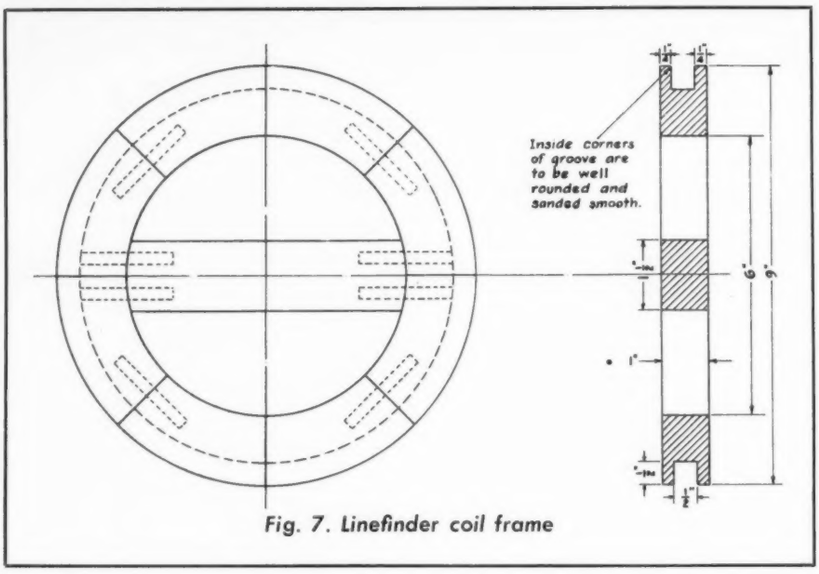


Fig. 7. Linefinder coil frame

From the study of the current flow to the line, K measured in this way is an average value of coating resistivity (linear) for a distance of about $10b$ each way along the line from S_1.

In making use of this method, there is no mistaking the electrical difference between a reasonably well-coated line and bare one.

In examining bare lines it is interesting to note that some of the "cathode scale" found in well-aerated soil is of rather higher resistance than the soil. In swamps the indicated value of K is sometimes negative. The interpretation of this is that a layer of corrosion products and soil salts have gathered next to the bare line, reducing the soil resistance near the pipe. This has the same result as though one used the wrong value of d for the line diameter.

The apparent value of d that must be used to make $K=0$ is called the "electrical pipe diameter." Examination of the relationship shows that the electrical diameter of a pipe line is very small for high values of K.

There is some question as to the value of ρ to use in calculating K, as ρ varies, generally downward, from the earth surface to the pipe depth and beyond. Under these conditions K/ρ is a good criterion of coating condition.

The difficulties mentioned are inherent in any method of *in situ* measurement of coating resistance. This is because the test current perforce must flow through a more or less non-uniform environment. Fortunately, in many especially corrosive areas where one is particularly interested in coating resistance, the value of soil resistivity is uniform enough to give reasonably satisfactory results.

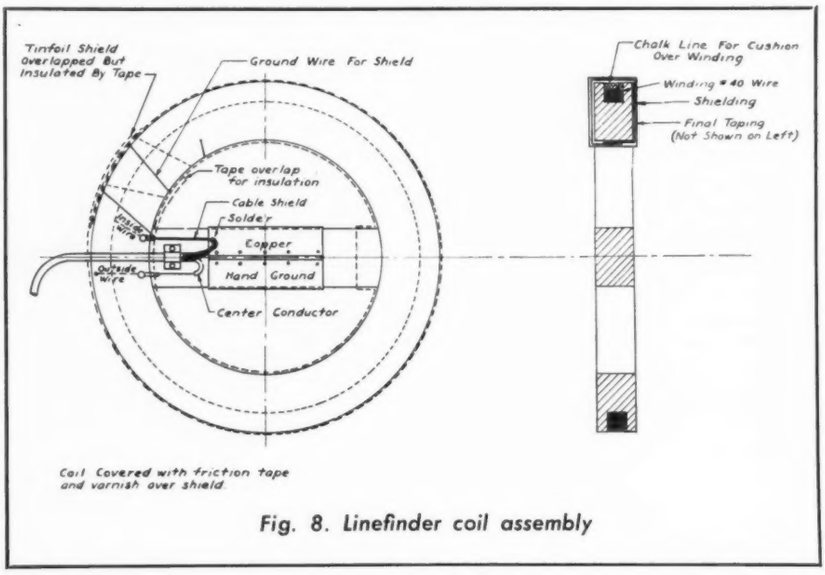


Fig. 8. Linefinder coil assembly

Current Density Determination

Current density is determined in the following manner[3]:

Let i = the average current in amp. per unit length of line, picked up.

ρ = ohm-ft. (if ft. is unit of line length) soil resistivity.

Then:

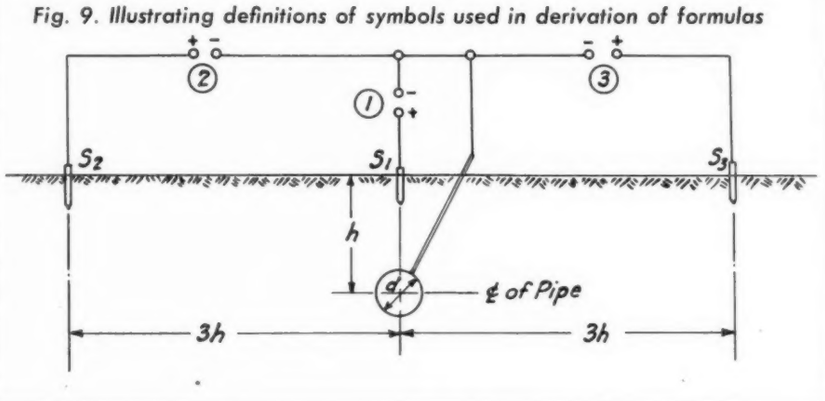
$$i = \frac{1.36I}{\rho}\,(R_2 + R_3 - 2R_0) \text{ amp. per ft.}$$

If very careful measurement is made of the distribution of anode current in the line, the value of i can be plotted as the tangent of the slope of the measured curve. The same method of reading "swings" must be used to untangle the anode amperes in the line from stray and galvanic currents.

Should these measurements be undertaken the above expression can be inverted to give the value of "ρ" to use in coating resistivity calculations.

[3]In Dr. Scott's paper (Loc. Cit) is an alternative method of current density measurement using only earth gradient increments, which is a more accurate method over good coatings (low coating conductance).

Fig. 9. Illustrating definitions of symbols used in derivation of formulas



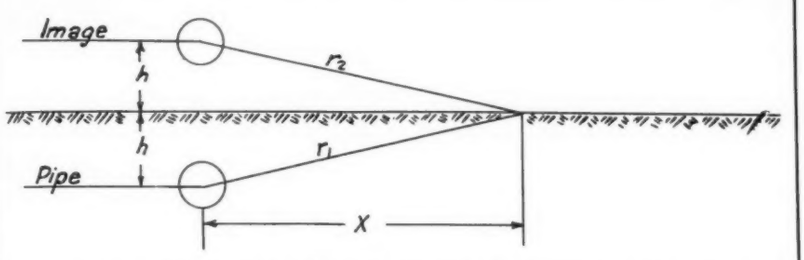


Fig. 10. Derivation of relationships involved in coating resistance measurement

Appendix

V = earth potential in volts, at distance x ft.

ρ = earth resistivity in ohm-ft.

i = current picked up from anode in amp. per ft. of line length

I = anode current in amp.

r_1, r_2 = radii from pipe and image, respectively, in ft. (see Fig. 10).

b = depth of centerline of pipe in ft.

A = outer radius of pipe in ft.

$d = 2A$ = pipe diameter

C = constant of integration

K = coating leakage resistivity, ohm-ft.

The general potential relationship is:

$$V = \frac{i\rho}{2\pi}\log_e r_1 + \frac{i\rho}{2\pi}\log_e r_2 + C$$

If we refer the measurements to the pipe metal as the zero of potential, then the earth potential where $r_1 = A$ and $r_2 = 2b$ is the IR drop in the coating, which is iK.[4] Consequently:

$$i\mathrm{K} = \frac{i\rho}{2\pi}\log_e A + \frac{i\rho}{2\pi}\log_e 2b + C$$

An obvious simplification results if we let $\mathrm{K} = \frac{\rho}{2\pi}\log_e \mathrm{M}$ where $\log_e \mathrm{M}$ = constant of proportionality.

Then $$C = \frac{i\rho}{2\pi}\log_e \frac{\mathrm{M}}{2Ab} = \frac{i\rho}{2\pi}\log_e \frac{\mathrm{M}}{bd}$$

Therefore:

$$V = \frac{i\rho}{2\pi}\left(\log_e r_1 r_2 + \log_e \frac{\mathrm{M}}{bd}\right)$$

Now: $r_1 = r_2 = \sqrt{b^2 + \mathrm{x}^2}$ so $r_1 r_2 = b^2 + \mathrm{x}^2$ (on earth's surface)

Consequently:

$$V_\mathrm{x} = \frac{i\rho}{2\pi}\left(\log_e (b^2 + \mathrm{x}^2) + \log_e \frac{\mathrm{M}}{bd}\right)$$

The coupling resistances are defined by:

$$\mathrm{R_x} = \frac{\Delta V_\mathrm{x}}{\Delta I} = \frac{\rho}{2\pi}\frac{\Delta i}{\Delta I}\left(\log_e (b^2 + \mathrm{x}^2) + \log_e \frac{\mathrm{M}}{bd}\right)$$

In the field we can measure $\mathrm{R_x}$, x, and ρ:

We want to find: $\frac{\Delta i}{\Delta I}$

= current pickup per ft. per amp. anode current

$\mathrm{Log_e\, M}$ = coating resistance factor

Take three couplings at $\mathrm{x} = 0$ and $\mathrm{x} = \pm \mathrm{n}b$ where n = constant. The average of $\mathrm{R_{+nh}}$ and $\mathrm{R_{-nh}}$ are used to eliminate sheet currents transverse to the line due to the anode.

Let

$$\frac{\mathrm{R_{+nh}} + \mathrm{R_{-nh}}}{2} = \mathrm{R_{nh}}$$

$$\mathrm{R_{nh}} = \frac{\rho}{2\pi}\frac{\Delta i}{\Delta I}\left(\log_e (\mathrm{n}^2 + 1) b^2 + \log_e \frac{\mathrm{M}}{bd}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\mathrm{R_o} = \frac{\rho}{2\pi}\frac{\Delta i}{\Delta I}\left(\log_e b^2 + \log_e \frac{\mathrm{M}}{bd}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Equation (1) divided by equation (2) gives:

$$\frac{\mathrm{R_{nh}}}{\mathrm{R_o}} = \frac{\log_e (\mathrm{n}^2 + 1)\, b^2 + \log_e \frac{\mathrm{M}}{bd}}{\log_e b^2 + \log_e \frac{\mathrm{M}}{bd}}$$

If we change to base 10, the factor 2.303 cancels out; expanding we get:

$$\frac{\mathrm{R_{nh}}}{\mathrm{R_o}} = \frac{\log_{10} b + \log_{10} (\mathrm{n}^2 + 1) + \log_{10} \frac{\mathrm{M}}{d}}{\log_{10} b + \log_{10} \frac{\mathrm{M}}{d}}$$

if we let

$\mathrm{n} = 3$, $\log_{10} (\mathrm{n}^2 + 1) = 1$

Therefore:

$$\frac{\mathrm{R_{3h}}}{\mathrm{R_o}} = \frac{1 + \log_{10} b + \log_{10} \frac{\mathrm{M}}{d}}{\log_{10} b + \log_{10} \frac{\mathrm{M}}{d}}$$

Solving:

$$\log_{10} \frac{\mathrm{M}}{d} = \frac{\mathrm{R_o}}{\mathrm{R_{3h}} - \mathrm{R_o}} - \log_{10} b.$$

or

$$\log_{10} \mathrm{M} = \frac{\mathrm{R_o}}{\mathrm{R_{3h}} - \mathrm{R_o}} - \log_{10} \frac{b}{d}$$

Now,

$$\mathrm{K} = \frac{\rho}{2\pi}\log_e \mathrm{M} = \frac{2.303\rho}{2\pi}\log_{10} \mathrm{M}$$

Therefore:

$$\mathrm{K} = 0.367\rho\left(\frac{\mathrm{R_o}}{\mathrm{R_{3h}} - \mathrm{R_o}} - \log_{10}\frac{b}{d}\right).$$

Subtracting equation (2) from equation (1) when $\mathrm{n} = 3$ results in:

$$\mathrm{R_{3h}} - \mathrm{R_o} = \frac{\rho}{2\pi}\frac{\Delta i}{\Delta I}\log_e \frac{10b^2}{b^2} = \frac{2.303\rho}{2\pi}\frac{\Delta i}{\Delta I}$$

as $\log_{10} 10 = 1$

Then:

$$\frac{\Delta i}{\Delta I} = \frac{2\pi}{2.303} \cdot \frac{1}{\rho}(\mathrm{R_{3h}} - \mathrm{R_o})$$

and

$$\frac{\Delta i}{\Delta I} = 2.73\left(\frac{\mathrm{R_{3h}} - \mathrm{R_o}}{\rho}\right)$$

which gives current density.

Referring now to the network measurements in Fig. 9, where we measure $\mathrm{R_1}$, $\mathrm{R_2}$, $\mathrm{R_3}$, and ρ we have:

$$\mathrm{R_{3h}} = \frac{\mathrm{R_2} + \mathrm{R_3}}{2} \text{ and } \mathrm{R_o} = \mathrm{R_1}.$$

Substituting gives:

$$\mathrm{K} = 0.367\rho\left(\frac{2\mathrm{R_1}}{\mathrm{R_2} + \mathrm{R_3} - 2\mathrm{R_1}} - \log_{10}\frac{b}{d}\right)$$

$$i = \frac{1.365I}{\rho}\left(\mathrm{R_2} + \mathrm{R_3} - 2\mathrm{R_1}\right)$$

where:

$\mathrm{R_1}$, $\mathrm{R_2}$, $\mathrm{R_3}$ = coupling resistances in true ohms

ρ = ohm-ft. soil resistivity

K = ohm-ft. coating leakage resistance (ohms leakage through one lineal ft. of coating)

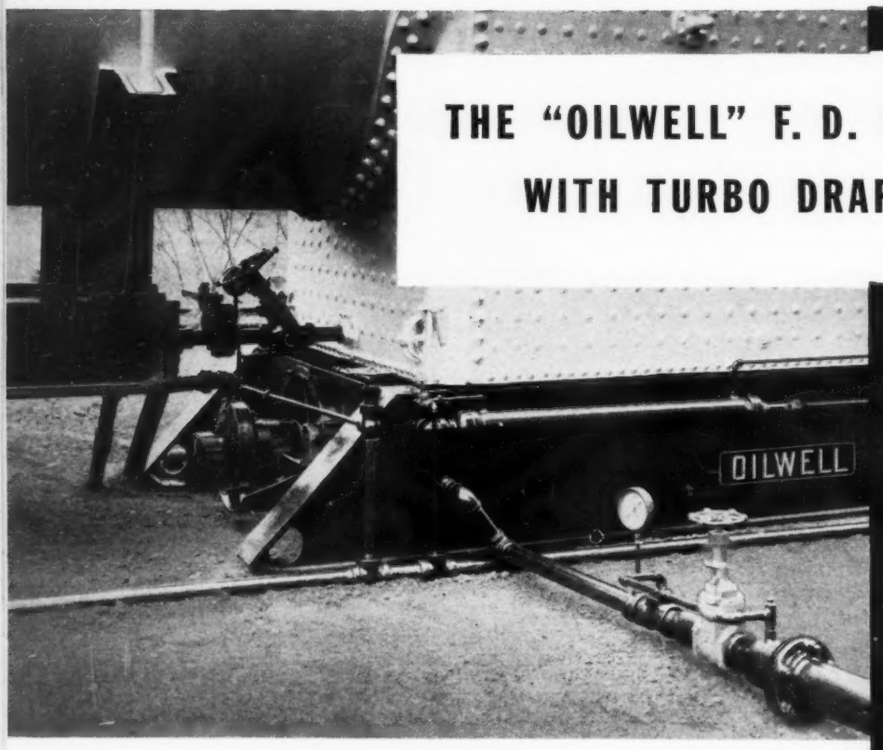
I = anode amp.

i = amp. per ft. picked up due to anode.

---

[4] In Dr. Scott's paper (loc. cit.) the use of $r_2 = 2h$-A, instead of $r_2 = 2h$ as here used, is the result of the choice of the path of approach to the line (directly down from the surface). Usually $\mathrm{A} \gg 2h$ so that the current distribution is almost uniform, the ratio of current density on top to current density on bottom of lines being given by $\frac{2h - a_1}{2h + a_1}$ where a_1 = electrical radius. This small lack of uniformity is due to the proximity of the earth's surface.

Time-Proved Design



THE "OILWELL" F. D. PORTABLE DUCK'S NEST WITH TURBO DRAFT-FAN AND BURNER

Using the time-proved, forced-draft method of firing, the "Oilwell" F. D. Portable Duck's Nest has repeatedly demonstrated money-saving advantages in the operation of oilfield steam power plants. The unit comprises a refractory-lined, welded, steel frame with built-in, steam-turbine driven draft-fan and burner arrangements for firing with either gas or oil or a combination of both. It can be furnished for locomotive-type oilfield boilers of any size or make.

ADVANTAGES . . .

Increases boiler output. In a furnace of ample volume, fuel and air are thoroughly mixed, causing early and complete combustion with no flames entering the tubes. Positive-pressure (provided by forced-draft) fills the entire firebox with the products of combustion and results in uniform flue-temperature.

Reduces transportation and installation costs. Entirely eliminates the use of stacks.

Saves fuel and water. Uses only a small percentage of the steam required for either a stack jet or a steam atomizer (for oil firing).

NEW INTERCHANGEABLE PARTS AND ACCESSORIES

keep "Oilwell" and Wilson-Snyder Steam and Power Slush Pumps modern and up-to-date

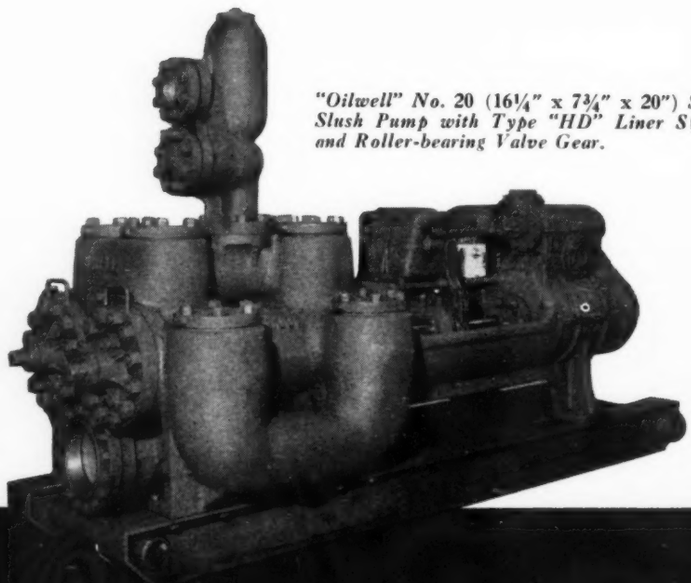
Constructed in accordance with time-proved design principles for oilfield service, "Oilwell" and Wilson-Snyder Slush Pumps *are not* made obsolete by subsequent improvements. As improvements are made they are incorporated in fully interchangeable parts and accessories which can be applied to pumps in service. Send now for information on the following new developments:

- ★ **Type "HD" Roller-Bearing Fluid Liner Spacers**
- ★ **Improved Type "C" Streamlined Valves and Seats**
- ★ **Roller-Bearing Valve Gear (for No. 20 and "Super" Steam Pumps)**

STEAM SLUSH PUMPS

	No. 16	No. 18	No. 20 (two sizes*)	"Super" (two sizes*)
Steam-Cylinder Diameter by Max. Liner Size by Stroke ..(Inches)	12x6 x16	14x7¼ x18	16¼x7¾ x20	16¼x7¾ x20
Number and Size of Suction Openings....	1-6"	3-10"	1-10"	3-10"
Hydraulic Test Pressure, Discharge .....(Lbs./Sq. In.)	2000	3000	4000	4000
Maximum Working Pressure, Discharge .....(Lbs./Sq. In.)	1200	1800	2500	2500
Maximum Steam Pressure..(Lbs./Sq. In.)	300	400	350	350
Normal Operating Speed .....(R.P.M.)	55	50	50	50
Theoretical Displacement at Normal Speeds .....(G.P.M.)	410	622	771	771
Stalling Load at Max. Steam Pressure ....(Pounds)	33,800	61,700	72,600	72,600
Gross Weight: Domestic.....(Pounds)	8,300	14,400	20,300	20,850
Export.....(Pounds)	8,800	15,000	21,200	21,800

**Both the No. 20 and the "Super" Pumps are also available with 15" diameter steam cylinders designed for a maximum working pressure of 400 lbs. per sq. in.*



"Oilwell" No. 20 (16¼" x 7¾" x 20") Steam Slush Pump with Type "HD" Liner Spacers and Roller-bearing Valve Gear.

Principles increase output and reduce operating cost of "OILWELL" Machinery

THE "OILWELL" NO. 64 UNIVERSAL HOISTING UNIT

Simplicity based on time-proved design principles makes this compact and portable hoisting unit outstanding in performance and low-cost operation. Features include:

Two speeds to the rotary and four to the drum.

Instantaneous reversing — steam-rig simplicity of controls.

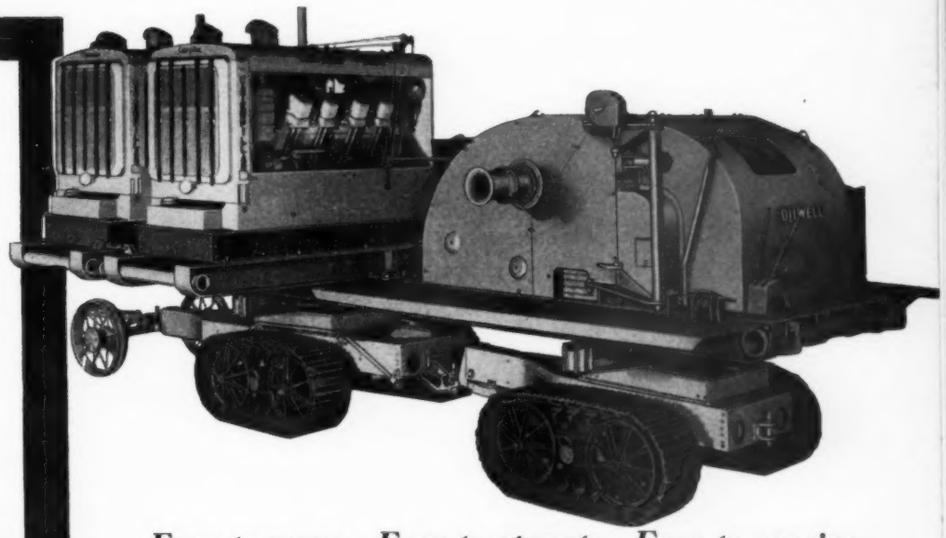
May be driven by either internal-combustion engines or steam and is easily converted in the field. Either one or two internal-combustion engines may be used, with a wide choice as to capacity, fuel and make. When two engines are used, a dual drive permits compound or separate operation.

Extreme flexibility in setting power pump is provided by idler pulley.

Friction-clutch rotary drive facilitates spinning pipe and saves time in making trips.

Roller chains and cut-tooth, heat-treated steel sprockets in sealed oilbath enclosures provide all speed reductions.

All grease lubrication fittings are grouped on a central panel.



Easy to move...Easy to operate...Easy to service

One of several similarly equipped and mounted "Oilwell" No. 64 Universal Hoisting Units recently shipped to a South American oil field. In service, the hoisting unit remains on its wagon mounting. A special derrick substructure permits backing the assembly into place.

SPECIFICATIONS

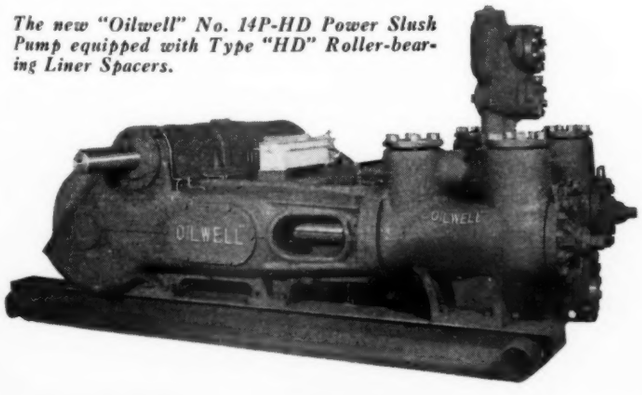
Recommended Max. Drilling Depth: with 4½" Drill Pipe (6 lines)..	(Feet)	5000
Recommended Max. Drilling Depth: with 3½" Drill Pipe (6 lines)..	(Feet)	6000
Drum: Spool Diameter	(Inches)	16
Width between Flanges	(Inches)	26½
Brake Rims, Diameter by Face Width	(Inches)	46x7¾
Length, Over-all	(Feet)	24
Height, Over-all	(Feet)	6½
Width, Over-all without Catheads	(Feet)	8
Weight, Complete for Internal-Combustion Engine Drive but less Engine and V-belts	(Pounds)	21,850

TWO *New* Power Slush Pumps to meet more severe drilling conditions:

☆ **"OILWELL" NO. 14P-HD (7¼" x 14")**

☆ **WILSON-SNYDER NO. 18-P (7¼" x 18")**

The new "Oilwell" No. 14P-HD Power Slush Pump equipped with Type "HD" Roller-bearing Liner Spacers.



Fully recognizing the increasing severity of operating requirements for power slush pumps, "Oilwell" and Wilson-Snyder have developed, time-proved, and introduced two sturdy new models. The complete line of "Oilwell" and Wilson-Snyder Slush Pumps (listed in the following table) includes a dependable pump of efficient size and ample capacity for every drilling need.

POWER SLUSH PUMPS

		No. 12-P	No. 612-P	No. 16-P	No. 14P-HD	No. 18-P	No. 20-P
Maximum Liner Size by Stroke	(Inches)	5x12	6x12	6x16	7¼x 14	7¼x 18	7¼x 20
Hydraulic Test Pressure, Discharge	(Lbs./Sq. In.)	2000	3000	3000	4000	4000	4500
Maximum Working Pressure, Discharge	(Lbs./Sq. In.)	1200	1800	1800	2500	2500	3000
Maximum Recommended Speed	(R.P.M.)	65	65	60	60	55	55
Maximum Working Pressure with Full-Size Liners at Max. Speed	(Lbs./Sq. In.)	540	520	520	765	765	825
Theoretical Displacement at Maximum Speed	(G.P.M.)	251	364	447	570	673	850
Maximum Recommended Brake Horsepower Input at Max. Speed	(H.P.)	92	129	159	300	353	480
Gross Weight with Short Skids: Domestic	(Pounds)	7500	10290	14785	23600	28700	44416
Export	(Pounds)	7900	10880	15393	24300	29700	45931

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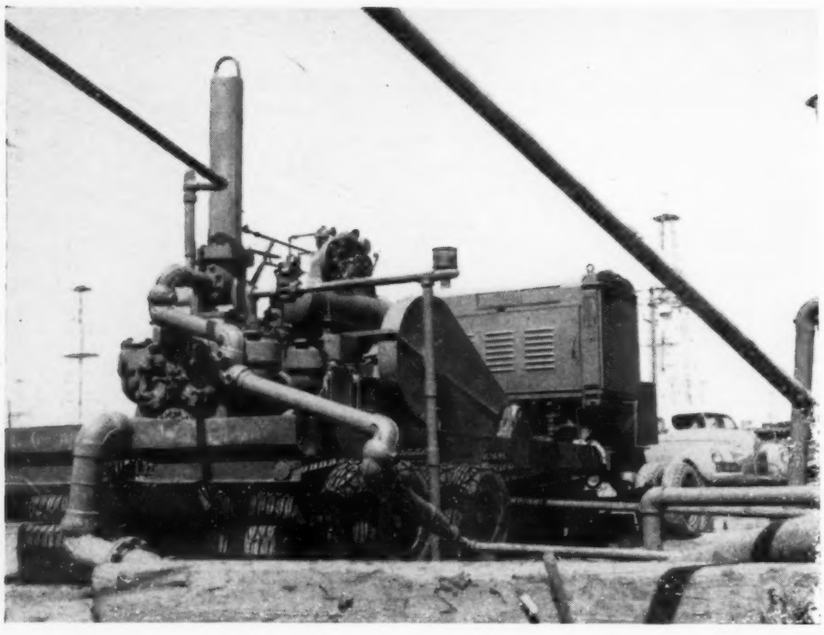

Portable butane-engine-driven mud pump used on numerous wells in Los Angeles Basin

Petroleum Engineer Exclusive

by
Wallace A. Sawdon
Pacific Coast and Foreign Editor

Portable Drilling Equipment—Design Features and Performance Data

☆ Lightweight rigs valued for general utility in drilling and well-servicing operations—Data on drilling and completion of California well are given

PORTABILITY of surface equipment for rotary drilling operations is obviously a desirable feature. Even the component parts of rigs used for deep drilling are now unitized to the greatest extent possible to facilitate rigging-up and transportation. For less heavy duty rigs are now provided with drawworks and prime movers unitized to fit structural steel foundations and many of the modern heaviest duty rig designs include structural steel substructures that are virtually portable units in themselves.

The degree of portability and the number of units comprising the drilling rig vary, of course, with size. In large power-driven outfits, the number of internal-combustion engines used is usually the factor governing ease of portability. Portable rigs as here considered, however, are those in which the drawworks and prime mover are mounted on trucks or tractors to form self-propelled units and, after being backed up to the derrick floor or otherwise positioned, operate from their setting on the truck or tractor. In some designs the drawworks may overhang the vehicle to permit partial support of the weight by the derrick floor. In others the rig unit may travel on tracks so that an extension of a few feet may be made to obtain support. In all cases, however, the completely portable drawworks and prime mover unit remains an integral part of the vehicle at all times.

Portable drilling rigs of this type are generally used for comparatively shallow wells although holes drilled to depths of 4000-5000 ft. are not unusual with such an outfit. Most of the prime movers employed have probably been gasoline engines but Diesel, natural gas, butane, and electric power have all been used to some extent. Portable masts as well as standard derricks have been used for the drilling operations; with the trend toward increased application of portable drilling outfits there has been a corresponding increase in the use of portable masts. Such masts, primarily designed for well servicing, have performed satisfactorily but at the present time manufacturers are developing masts more adaptable to drilling wells to 4000- or 5000-ft. depths.

Considering the present application of portable rotary drilling rigs, economy of transportation and decrease of rigging-up time are probably the outstanding features. Both new wells and redrilling or deepening operations are now being done with portable outfits and the performance possible during the drilling of a new well is indicated by an example given later that shows the adaptability of a portable rig in meeting a variety of requirements. In drilling new wells a further economy can be obtained by planning the site to take care of production equipment as well as the portable drilling rig. This is true whether a derrick or portable mast is to be used for the drilling operations.

In making the plans for a new well the concrete slab to be left permanently at the well can be laid before the hole is drilled. In addition to providing for foundations for the pumping unit to be installed either upon completion or at a later date, I-bolts can be set to provide for anchoring the portable rig during drilling and for similar anchoring of clean-out hoists or portable drilling equipment that may subsequently be used for repair work.

When tie-down bolts are thus installed they can be as readily used

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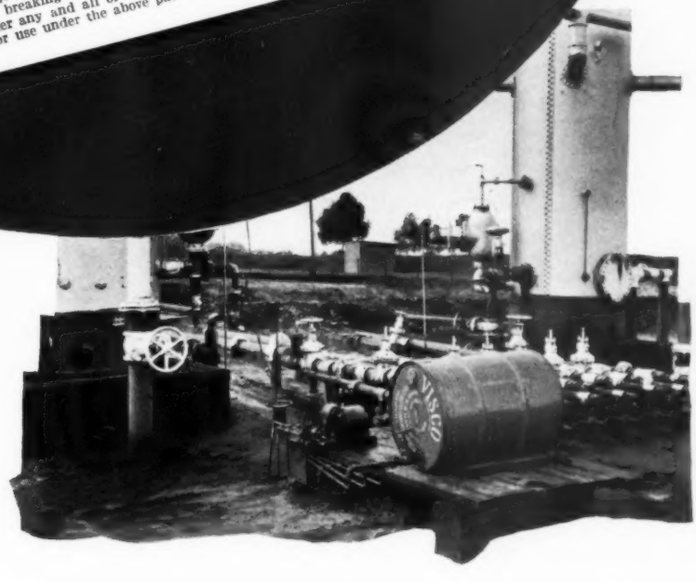

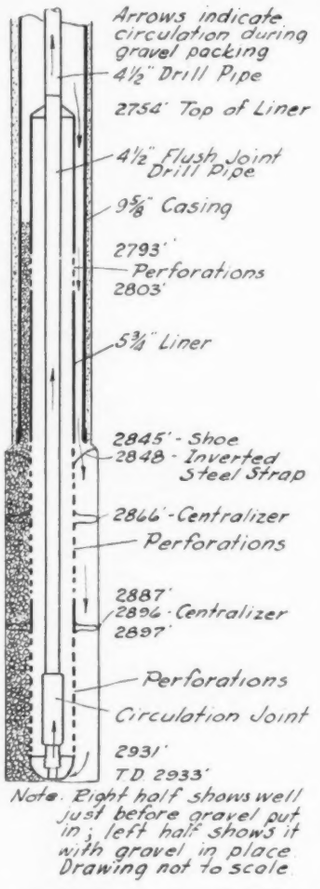

Fig. 1. Diagram of well drilled in Long Beach field, California, with portable hoist equipped with sand reel and rotary drive attachment

whether the drilling is done with a derrick or with a portable hoist. If such are not available, as is almost always the case on a redrill or deepening job, the drawworks is anchored by chains passed around the sill of the floor originally used for drilling the well. Actual conditions will obviously require different means of anchoring but this is a problem easily solved. Particular designs of portable masts usually take care of tie-down of the rig in addition to provision for guy wires necessary for support of the mast itself.

Adaptability

The adaptability of portable equipment both for drilling and for repair or cleanout operations is often a feature worthy of consideration. Rotary drive attachments can generally be applied to service hoists but it may not always be economical to have one rig capable of drilling to 3000 or 4000 ft. and use it for general service work. The rig capable of drilling to depths desired may be too big for the type of service work generally necessary at those depths. When operations over a certain area are extensive it may be better to have a cleanout hoist assigned to service work and confine a portable drilling outfit to drilling. Under other conditions, however, it may be advantageous to utilize the equipment ordinarily employed for service or repair work on drilling new wells between jobs. The extent of territory that the portable equipment has to cover, the amount of service work demanded by producing wells, field development requirements, and the capacities necessary for different classes of work will have to govern the number and sizes of portable units made available. Judicious consideration of all factors will influence greatly the employment of portable equipment from an economic standpoint.

Mud is circulated with engine-driven power pumps mounted as separate units for portable-rig drilling. In many cases, however, these units have been carried by truck to the location and then set on sills on the ground. Many of these units are now being mounted permanently on trailers; some of these completely portable units have been employed not only for mud circulation with portable drilling rigs but have served as auxiliary pumping equipment for deeper drilling operations when a main pump has been installed in the conventional manner.

Complete portability for all the surface equipment used in developing a specific area has been obtained by one oil company operating in a San Joaquin Valley, California, field by mounting a derrick, drawworks, and engine on one portable floor. The derrick is of the regular 4-leg type approximately 80 ft. in height. The floor, including the rotary machine, is moved on caterpillar-type treads placed at the four corners. During drilling, the floor is jacked up to relieve the stresses on the wheel and tread mechanism. Bolted to the edge of the floor and opposite the drawworks during drilling is a portable pipe rack that is mounted in a similar way.

After a well is drilled with this equipment the derrick-rig unit is unbolted from the pipe rack unit, each hooked on to a truck or tractor and transported to the next location. The slush pump is, of course, permanently mounted on its own trailer and with everything on wheels the entire surface equipment is set up within a few hours on the next well to be drilled. The topography of the field where the equipment is now being used is hilly but this seems to offer no transportation difficulties. The wells drilled are approximately 2000 ft. in depth. The same equipment was also used in a Coastal field where it drilled five 1300-1450 ft. wells in five weeks.

Performance

The well illustrated by Fig. 1 was drilled in the Long Beach, California, field with a portable hoist equipped with sand reel and rotary drive attachment. Although the total depth was slightly less than 3000 ft. the operation included wall scraping the hole and gravel packing the liner by the reverse circulation method after it was run.

A 122-ft. steel derrick was used for the drilling operations. The hoist was of the heavy-duty type and powered by a 220-hp. gas engine. The drawworks-engine unit was permanently mounted on a truck equipped with self-contained tracks that provided for moving the unit outward a few feet to obtain partial support on the derrick floor where it was anchored to tie-bolts set in a concrete production mat previously built below the derrick floor. Mud was circulated by a 7¼ by 12 mud pump driven by a gas engine.

A 12¼-in. hole was drilled to a depth of 2845 ft. and a 10⅝-in. hole from there to 2933 ft. Three rock bits, including one for reaming, were used

One type of mast developed for drilling with portable equipment

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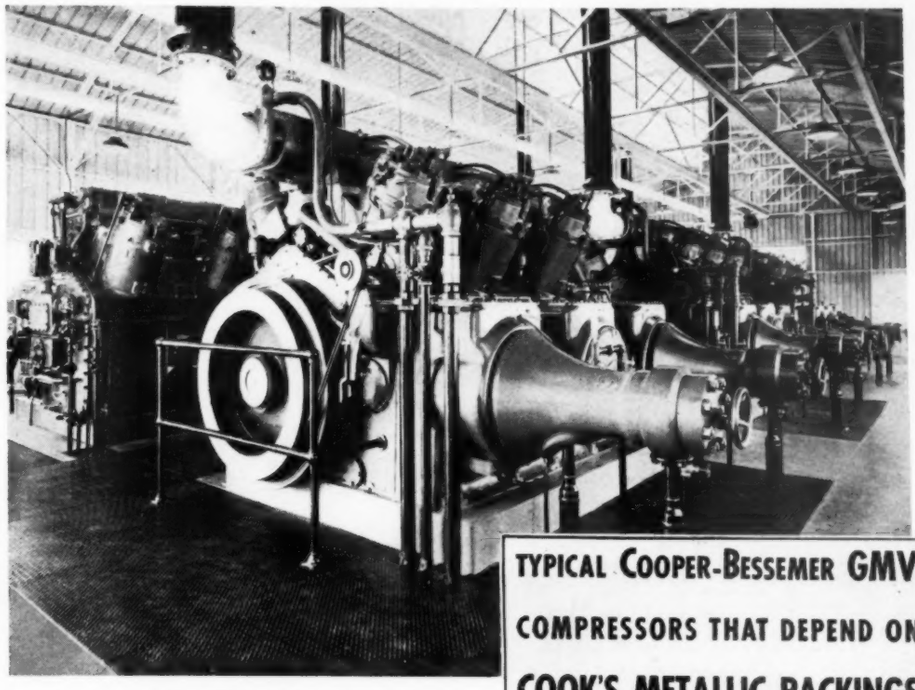

Photo courtesy Cooper-Bessemer Corp.

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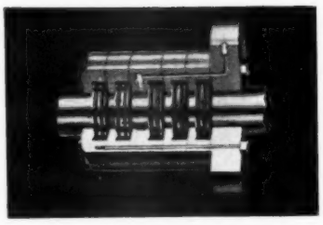

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And this preference is not confined to high pressure units. For over 50 years, COOK'S Metallic Packings have been first choice with leading builders and operators of all types of engines and compressors. They earned this preference and have held it year after year by outstanding superiority in performance. Builders and operators alike have learned that the **unequalled sealing and wear-resisting properties** of COOK'S Metallic Packings, which make their use profitable where conditions demand the best, are equally effective in helping **any** engine or compressor to operate at maximum efficiency with minimum upkeep expense.

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to drill the 12¼-in. hole but the entire 10⅝-in. hole was cored, using one rock core head and three conventional drag-type core heads. The drill string consisted of 4½-in. drill pipe and 90 ft. of 8⅛-in. drill collar. After running an electrical log and cementing 9⅝-in. flush-joint casing at 2845 ft., the 10⅝-in. hole was wall-scraped to 15-in. diameter to provide for the gravel packing. Three sets of 15-in. wall scraper blades were used for this hole enlargement.

The well was completed in a total of 14 days with the following time distribution:

Drilling	4 days
Coring	2 days
Reaming	1 day
Running casing, testing, etc.	3 days
Wall scraping	2 days
Gravel packing, washing perforations	1 day
Running tubing, rigging up pump	1 day
Total	14 days
Total drilling time on bottom	46.00 hours
Total coring time on bottom	10.75 hours
Total	56.75 hours

The well was completed with 3-in. tubing set at 2740 feet.

The mud fluid was kept in condition at all times during drilling. From the surface to a depth of 2820 ft. the weight was 76 lb. per cu. ft. with viscosity of 56.6 sec. Marsh funnel. The amount of mud used in this distance was 315 bbl. with one change. From 2820 ft. to 2933 ft., the weight was 76.5 lb. per cu. ft. with viscosity of 37.5 sec. March funnel. The amount here was 639 bbl. with two changes. The mud used while wall-scraping was 70.5 lb. per cu. ft., viscosity 40 sec.

The 9⅝-in. casing was made-up with a cementing sleeve at 726 ft. so that the string could be cemented at that point as well as around the shoe. The shoe was a float shoe equipped with a 15-ft., 3½-in. drillable metal stinger.

In cementing the casing a 6-in. by 6-in. by 15-ft. wooden spacer preceded the bottom plug as neither a float collar nor a baffle plate were used above the shoe. Cementing around the shoe at 2845 ft. was done with 250 sacks and after this was in place 200 sacks of cement were pumped through the cementing sleeve at 726 ft. to cement the upper portion of the casing. After the cement had set, the hole was cleaned out 5 ft. below the shoe for a water shut-off test.

After the hole had been wall-scraped to 15-in. diameter from the casing shoe to bottom, 179 ft. of 5¾-in. liner was run in the enlarged hole extending 91 ft. into the casing, making the top of the adapter at 2754 ft. This liner was perforated from 2931 ft. to 2897 ft.; from 2887 ft. to 2844 ft.; and from 2803 ft. to 2793 ft. The purpose of the blank section from 2887 ft. to 2897 ft. was to provide a space for future plugging operations; that of the blank section from 2803 ft. to 2844 ft. (inside the casing) was to allow a reservoir for excess gravel. The perforations from 2793 ft. to 2803 ft. were to act as an indicator and help determine the top of the gravel between the casing and liner. The blank section at the top of the liner was designed to extend above the calculated height of the gravel and thus permit extra space to drive a 5¾-in. by 9⅝-in. adapter into position without it resting on or coming in contact with the gravel.

Portable mast with capacity of 200,000 lb. when extended 90 ft. Used for drilling with portable rig this should handle about 5000 ft. of 4½-in. drill pipe.

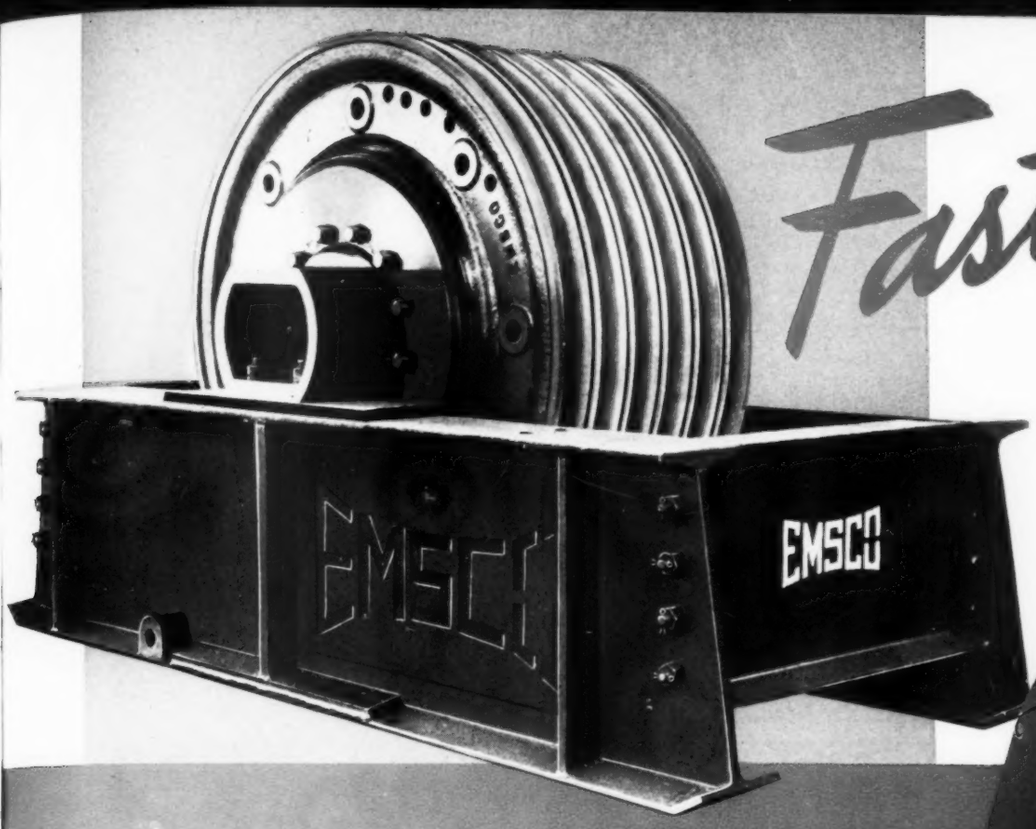
The liner was centered with 4 spring guides attached at 2896 ft. and 2866 ft. In addition there were 4 pieces of ¼-in. by 1-in. by 18-in. spring-steel straps welded to the liner in inverted position at 2848 ft. to prevent the liner from being pulled out of the hole when the wash pipe was removed. These springs also served as an anchor to hold the liner in position when cleanout tools or swabs are run at a later date. A special nipple approximately 3½ in. long was attached to the top of the liner with two brass shear pins. On top of this nipple was a bonnet with a retainer containing hydraulic packing. The assembly was friction-tight around the wash pipe and prevented gravel from entering the top of the liner. Also attached to the nipple were three metal fins that centered the liner within the casing. The drill pipe on which the liner was run was packed-off at the surface with a blowout preventer.

The gravel-packing equipment was assembled in the liner on the derrick floor. On the bottom was a shoe in which was a left-hand connection, box up. A circulation joint was screwed into this; and subbed to the top of the joint was special 4½-in. flush joint drill pipe that extended to the top of the liner where it was subbed to the 4½-in. drill pipe previously used to drill the hole, this drill pipe continuing to the surface. At the bottom of the wash pipe was a 3-ft. rubber packer friction-tight to the inside of the liner.

After establishing reverse circulation the first batch of gravel was put in. The initial rate of gravel placement was 6 cu. ft. in 16 minutes with the pump running at 22 strokes per minute. This rate was increased during the run to 6 cu. ft. in 8 minutes with the pump at 32 strokes per minute. The placement pressure during the job increased from 50 lb. per sq. in. at the beginning to 175 lb. per sq. in. at completion.

After all the gravel was in, the operations were shut down for about an hour to allow the gravel to settle. The circulation joint was then unscrewed and pulled up inside the blank section of liner at 2825 ft. and normal circulation started. The circulation pressure was found to be 450 lb. per sq. in. The circulation joint was raised to test the perforations from 2803 ft. to 2793 ft. The pressure remained constant at 450 lb. per sq. in. and thus indicated that gravel had filled to the desired height.

The wash pipe was then raised to 2754 ft., shearing off the shear pins and raising the bonnet. The pressure reduced to 100 lb. per sq. in. and after maintaining circulation for awhile approximately 1 cu. ft. of gravel returned to the surface, leaving 95 cu. ft. in place. The gravel was injected by means of two chambers, each holding 6 cu. ft., and their alternate use gave continuous placement. The perforations were cleaned with a washer in 3½ hours.



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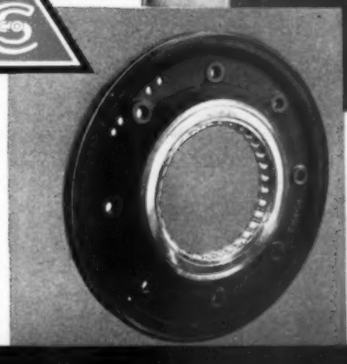

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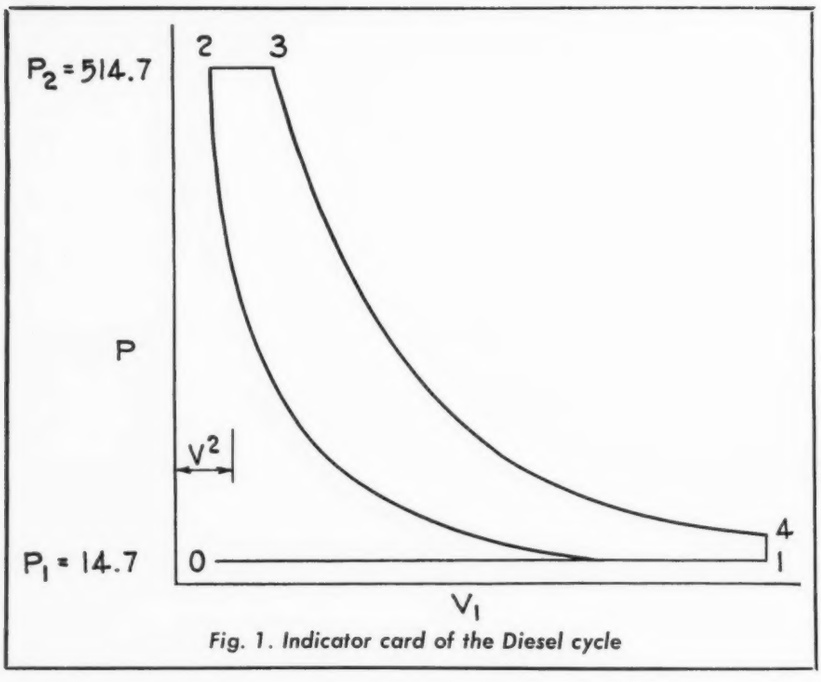


Fig. 1. Indicator card of the Diesel cycle

PETROLEUM ENGINEER Exclusive Feature

By

Orville Adams

☆ Consideration of heat transfer between cylinder walls and fuel charge all-important in design

Calculations Involving Diesel Cycle Simplified by Charts

IT should be borne in mind that all internal-combustion engines operate within the limits of two adiabatic processes, compression and expansion, with the input and ejection of the heat taking place between them. It should be remembered that the compression is required (a) to increase the efficiency of the engine, and (b) to increase the total amount of power that can be produced from a given cylinder size.

One purpose of compression is to heat the air charge before any heat is added by the combustion of the fuel in the Diesel engine. This function requires detailed study of certain factors not involved in the operation of the Otto cycle engine. From the Carnot cycle, it is learned that the higher the temperature at which heat is supplied, the greater the proportion of the heat added that can be converted into mechanical work. For example, a gas engine compresses the charge to only 90 lb. per sq. in., which results in a temperature at the end of compression of only 460°F., giving an efficiency of about 25 percent, representing the percentage of the heat actually converted into work. In the case of the Diesel engine with a compression pressure of 500 lb. per sq. in., the temperature at the end of the compression is more than 1000°F., and the efficiency is 35 to 39 percent. Although there are other factors that enter into the thermal efficiency, this difference in the compression temperature of 460°F. for the gas engine as compared with 1000°F. for the Diesel is the most important element contributing to the higher efficiency of the Diesel engine. The higher expansion ratio of the Diesel is another important factor accounting for its greater efficiency, this being also in relation to the higher temperature at the end of compression. As the internal-combustion engine can do work only by the use of heat between the compression and expansion steps in the process, there has been much study and research concerning the method of applying the heat after the compression has been built up.

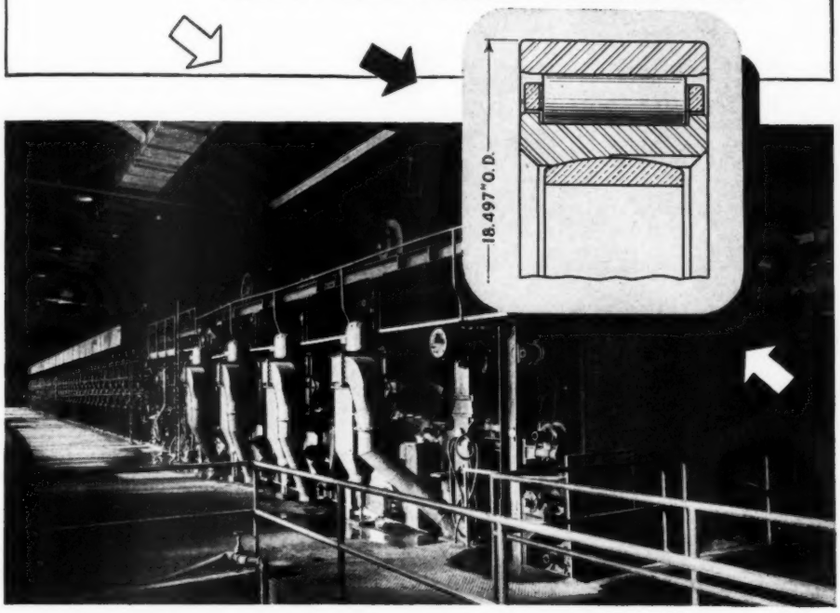
The principal limitation of the gas engine is that the heat is supplied and liberated so rapidly, by the combustion taking place so suddenly, that the piston is virtually motionless at top center while a major portion of the explosion and burning is taking place. Hence the name "constant volume" process. In the Diesel engine, however, particularly in the air injection Diesel engine as originally developed by Dr. Diesel, the fuel is burned at such a rate that the piston has had time to move away from top dead center, and the volume, instead of remaining constant, increases from point 2 to point

ORVILLE ADAMS

was educated at Kentucky State College and served in the technical branch of the army during the World War—After his discharge from the service he was for ten years sales engineer for Diesel engine manufacturers—Since 1930 he has devoted his time largely to the writing of text books and articles for leading technical journals—Is the author of authoritative text books on the Diesel engine that are widely used in technical schools, and at present is preparing a text on Diesel engine thermodynamics for college use—Is also engaged in research and investigation and the preparation of engineering reports on Diesel engine applications.

IN THE NEWS

WITH BANTAM BEARINGS



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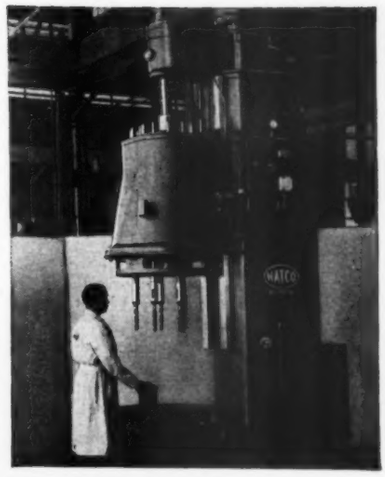

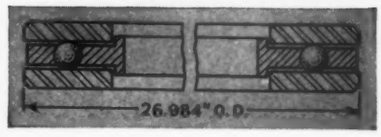

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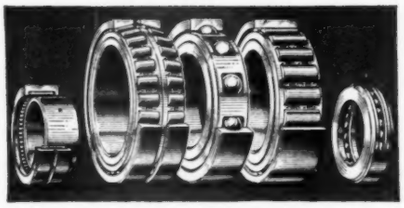

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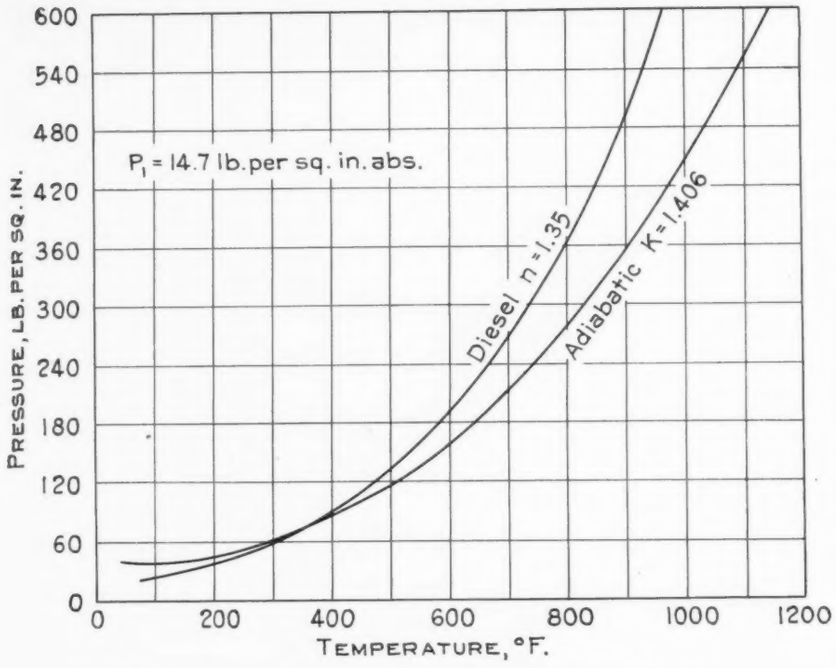


Fig. 2. Temperature-pressure relationships during compression

3 in Fig. 1 at practically constant pressure. The rate of fuel injection and the degree of atomization can be so adjusted that the pressure will remain almost constant, or in general practice show a slight variation above the compression pressure of about 10 percent. Only a few of the early Diesel engines actually developed such a constant pressure. It is for this reason, however, that the method of supplying the heat between the adiabatic processes of compression and expansion in the Diesel engine received the name of "constant pressure."

It is remembered that in both the constant volume and constant pressure processes the temperature increases in accordance with the law:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}. \quad (1)$$

It is obvious that constant pressure combustion can never actually be realized or practically attained in the actual Diesel engine but is only a standard or ideal condition for comparative purposes. Most Diesel engines operate partly at constant pressure and partly at constant volume, with many of the high-speed compression-ignition engines of today operating at virtually 100 percent constant volume.

Simplified Calculctions

The calculations involving the pressure, volume, and temperature of an adiabatic process can be simplified and made clear without resorting to highly complex mathematical processes. This is accomplished by carrying out the calculations relative to volume quantities as independent variables, and considering the pressure and the temperature changes in the process to be effects resulting from the changes in volume. The first step is to find the ratio of the volume occupied by the air before the beginning of the compression, to the volume at the end of compression. This is the ratio of V_1, the volume swept by the piston plus the clearance volume, to the clearance volume, V_2, to which the charge is compressed when all the air is in the clearance space at top dead center.

If we denote the cylinder volume (stroke × piston area) as V_d and the clearance volume as V_c, then this ratio of volumes may be denoted by the expression:

$$\frac{V_d + V_c}{V_c}$$

which is the same as V_1/V_2. By means of this formula the ratio can be directly changed into the ratio of absolute pressure by raising it to the 1.33 power through simple calculation, viz:

$$\left(\frac{V_d + V_c}{V_c}\right)^{1.33} = \frac{\text{C.P.} + 14.7}{14.7}. \quad (2)$$

in which C.P. = compression pressure.

For example, an engine with a clearance volume of 1/13 of the volume swept by the piston, which is considered as equal to 1, the ratio of absolute pressure would be, substituting the figures:

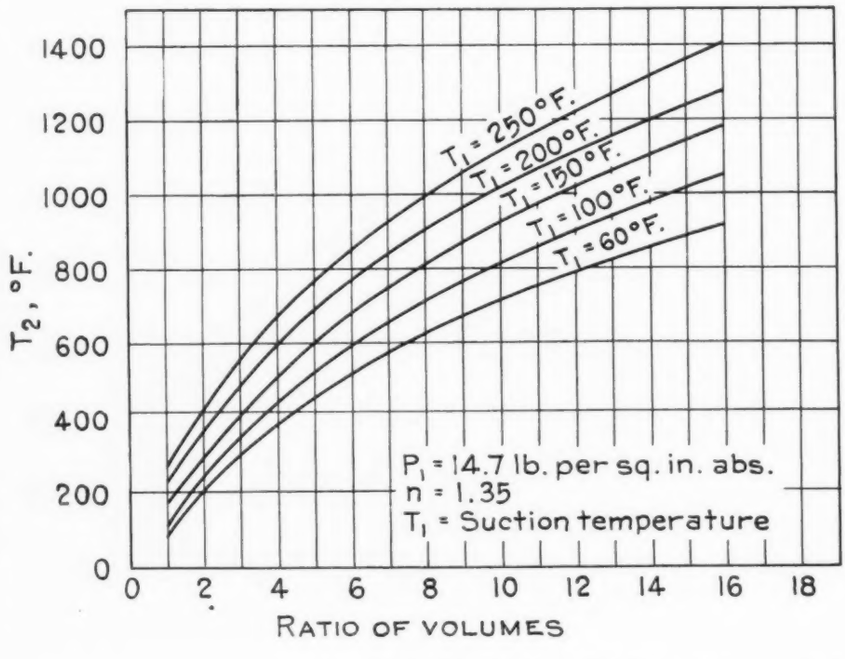
$$\left(\frac{1 + \frac{1}{13}}{\frac{1}{13}}\right)^{1.33} = (14)^{1.33} = 33.5 = \frac{\text{C.P.} + 14.7}{14.7}$$

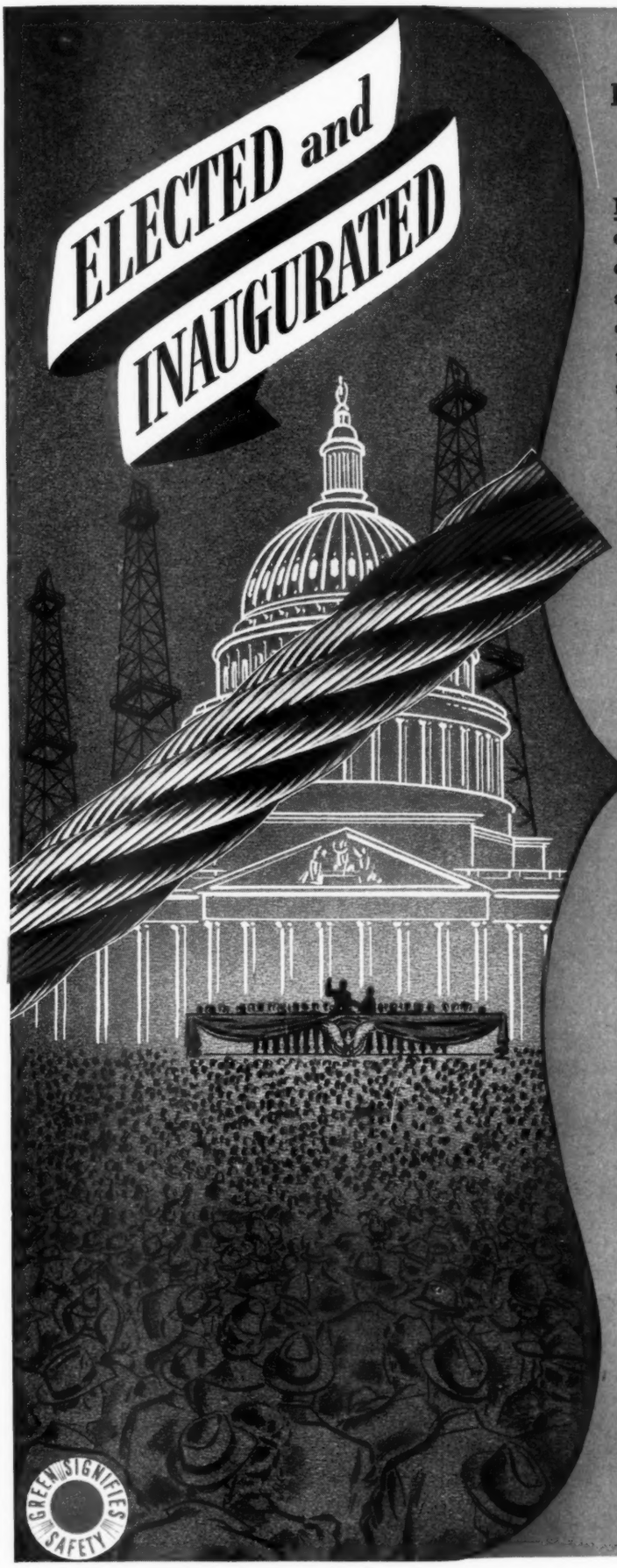
This simple equation and method is then solved by multiplying both sides by 14.7:

$$\text{C.P.} + 14.7 = 14.7 \times 33.5 = 492.5$$

Then by transposing 14.7, it is found that the compression pressure would be equal to 492.5 — 14.7 = 477.8 lb. per sq. in. It is then evident that the temperature change produced by the adiabatic volume change can be determined by this simple method, as it is

Fig. 3. Temperature-volume relationships showing ratio of volumes against T_2 for various values of T_1





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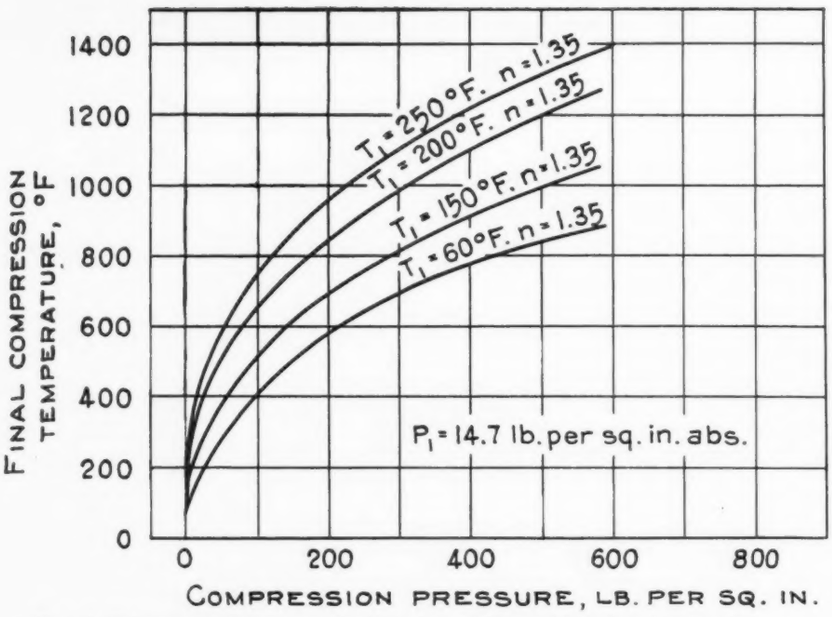


Fig. 4. Compression pressure-temperature relationships showing final T_2 plotted against compression pressure for the various values of T_1

also a function of the formula for volume ratio given above. This ratio is transformed by raising it to the 0.33 power, and would be:

$(14)^{0.33} = 2.39$.

For example, if the air at the beginning of the compression has a temperature of 100°F. in the cylinder, its absolute temperature would be $100° + 460° = 560°$F. abs. $= T_1$. This is then increased by the compression to T_2 ($560 \times 2.39 = 1338°$ abs.), equivalent to an increase of 879°F. (1339 — 460). This temperature is sufficiently high to ignite the fuel in a solid-injection Diesel with open combustion chamber, but it would be somewhat low for an air-injection Diesel engine. A temperature increase of 850°F. or more is usually sufficient to ignite the fuel in any engine unless the fuel has a low cetene number or the fuel is poorly atomized. Air-injection engines suffer a chilling effect from the expansion the atomizing air, but if the mixture, including the air charge and the expanding or atomizing air, averages 850°F. good ignition can be expected. The compression temperature in the air-injection engine must be higher to compensate for this chilling effect and still have the required 850°F. in the combined mixture. The importance of the temperature T_2 at the end of compression should not be overlooked in considering the performance of the engine, and T_2 should always be considered in making calculations.

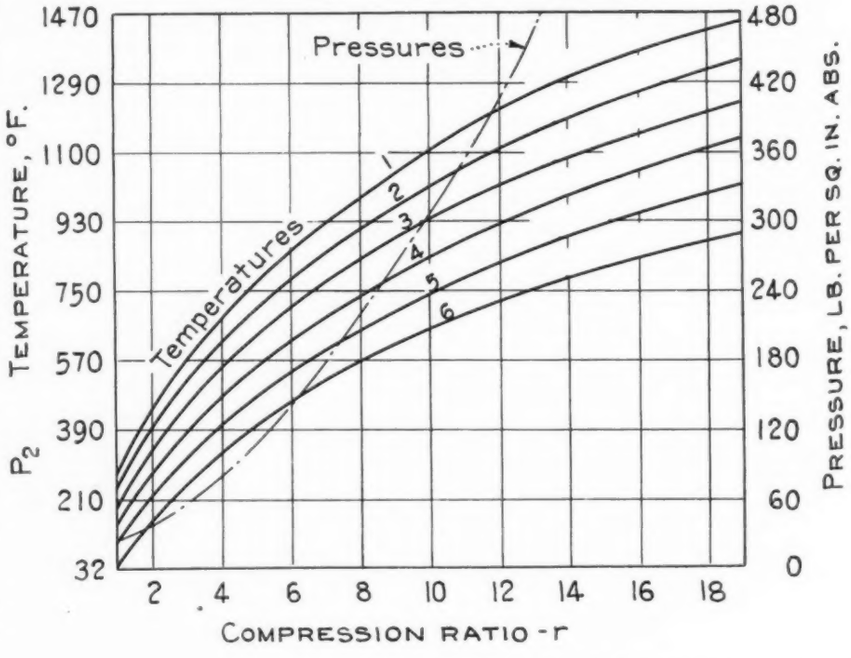
The compression and expansion processes taking place in the cylinder of a Diesel engine, involving simultaneous changes in the pressure, volume, and temperature of the working substance are generally viewed as a series of related steps that encompass the so-called gas processes occurring during the complete cycle. Referring to Fig. 1, the following points should be noted:

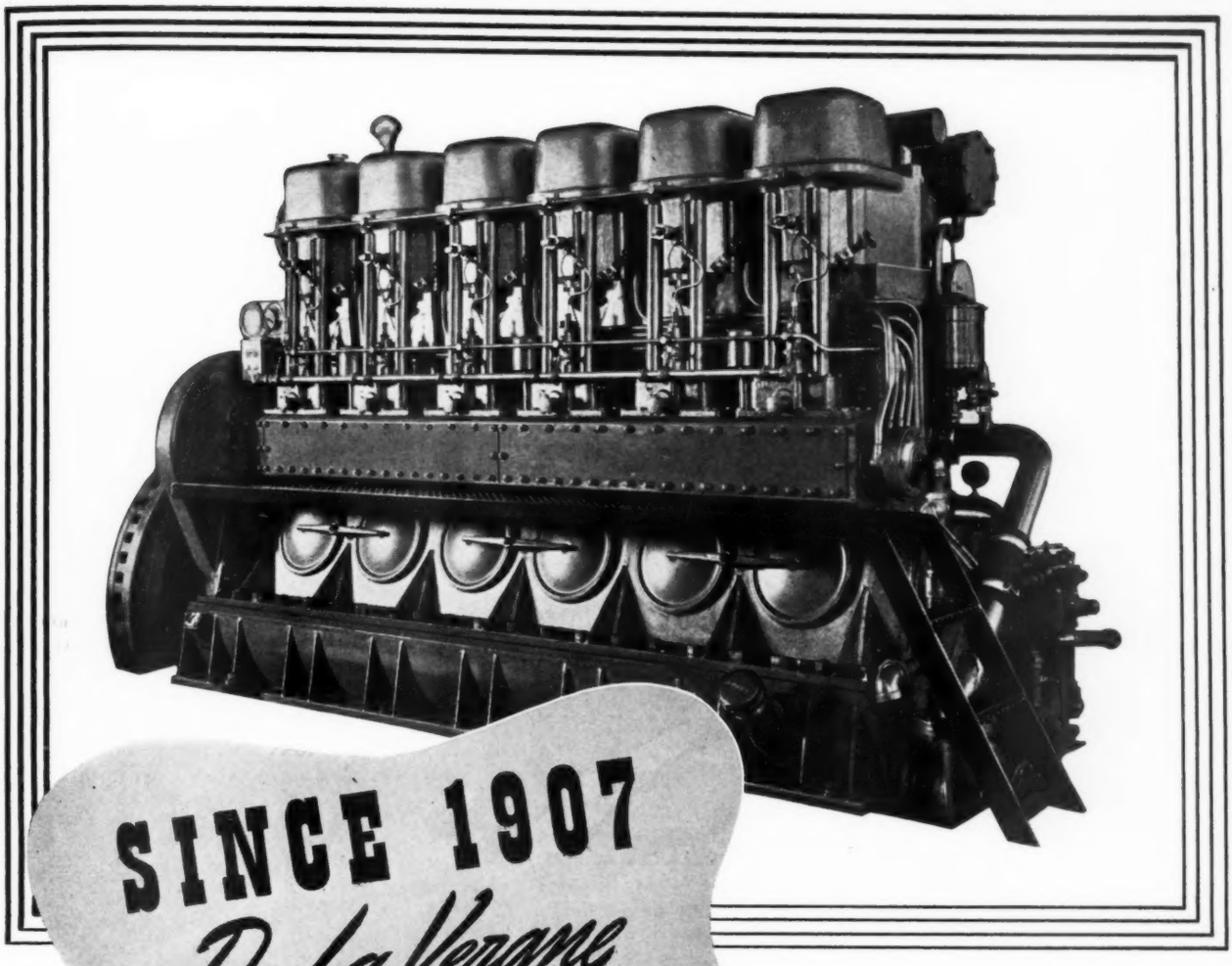
1. At the beginning of the compression stroke, the compression of the air begins at atmospheric pressure, or slightly below, designated as p_1, Fig. 1. The temperature, T_1, of the air at p_1 is somewhat higher than the surrounding air, due to the heat absorbed from the valves, piston heads, and cylinder walls. The volume occupied by the air charge in the cylinder at this point is the swept volume of the cylinder plus clearance volume, and is denoted as V_1.

2. When the compression stroke is completed at top dead center (point p_2), the volume in the cylinder has been reduced to that of the clearance volume V_2, the charge then being confined within the clearance space. In the meantime, the pressure has been increased to approximately 500 lb. per sq. in. gauge or an absolute pressure, P_2, of 514.7 lb. per sq. in. abs. The temperature, T_1, of approximately 80° has been increased to an absolute temperature, T_2, of approximately 1610°F. abs. (1150° + 460°), as a result of the compression stroke. These values only approximate actual conditions and are subject to reasonable variation.

3. The compression is considered adiabatic, as it occurs in such a short time that very little heat is gained or lost by the air in contact with the cylinder walls while the compression is occurring. Theoretically there is no heat change at all as the process is usually considered truly adiabatic. According to the law $PV^k = a$ constant, and as shown in Fig. 2, the value of $k = 1.406$. In an actual engine taking in air at normal atmospheric temperature, the first part of the compression stroke occurs when the temperature of the metal in the cylinder

Fig. 5. Final temperatures and compression pressures correlated with compression ratios at different values of T_1





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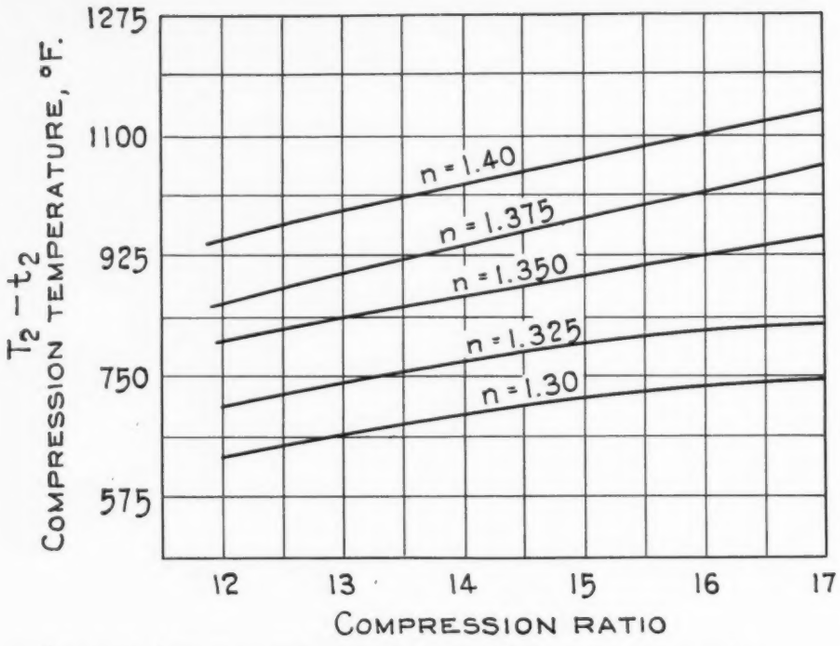

Fig. 6. Final compression temperature, T_2, plotted against compression ratios at various values for n

wall (which averages 300° to 400°F. during normal operation) is much higher than the temperature of the incoming air. During the last part of the compression stroke, the temperature of the air charge has been increased to about 100°F., which is higher than the cylinder wall temperature, and the air charge gives up a certain amount of heat to the walls.

4. The temperature of the air charge at the beginning of the compression stroke may vary from 30° to 80° above atmospheric temperature. Assuming an average atmospheric temperature of the air charge, the air temperature in the cylinder will usually be 80° to 160°F. at the start of compression. The effect of the intake air temperature, T_1, upon the final temperature, T_2, is shown over a wide range in Fig. 3. In these calculations the exponent of compression and expansion, n, is assumed to be 1.35 and p_1 is 14.7 lb. per sq. in.

5. The piston head temperature varies from 350° to 550°F. under varying load conditions, the cylinder wall temperature varies from 250° to 400°F., and the temperature of the cylinder head varies from 350° to 500°F. The air at the end of the stroke is usually at a temperature of 850° to 1050°F. As shown in Fig. 3, T_2 depends upon the various values of T_1 plus temperature effects of the metal parts. Averaging the temperature conditions with respect to the values of T_1 and T_2 it can be seen that these factors will usually be within the following limits:

$T_1 =$ 80° to 250°F.
$T_2 =$ 850° to 1150°F.

Inasmuch as the average temperature of the metal parts exposed to the air in the cylinder is 350° to 400°F., there is more heat lost to the cylinder wall during the compression than is gained by the air from the metal walls. This condition is greatly aggravated by the turbulence of the air at the end of the compression when the air is made to swirl about the combustion space. This greater loss of heat is definitely shown by the fact that the exponent, k, for the adiabatic process, which is about 1.400 from 100° to 1000°F. is actually found to be between 1.32 and 1.35, the value for n under actual conditions. For example, the exponent for polytropic processes is shown as $n = 1.35$ in Fig. 2, on account of the loss of more heat from the air to the walls than is gained by the air from the walls during the compression process. It has been estimated that the loss to the walls is 2 to 3 times the heat gained in the early part of the compression stroke. This loss is more pronounced and increases in the case of engines with complicated chambers and air cells on account of turbulence and air swirls.

6. The expansion portion of the cycle, although not entirely free of heat losses, can also be said to be somewhat nearer adiabatic, and is calculated as above. Although the process of expansion in the actual engine departs from the true adiabatic when the combustion is imperfect, retarded, erratic, or incomplete, when there is complete combustion in the highly developed Diesel engine, the expansion closely resembles true adiabatic. The value of n for the expansion curve would then be above the value of n for the normal compression curve. This would make the engine more efficient the nearer the value of n is to the adiabatic k. The relationship to efficiency is shown in Fig. 6, which gives the effect of the various values of n for the various compression ratios with respect to the effect upon compression temperatures, T_2. The same would apply for expansion.

The temperature-pressure relationships in the Diesel engine shown in Fig. 2, indicate how the loss of heat prevents adiabatic compression. The value of n is assumed to be 1.35 for this chart, just as in the usual formulas for temperature relationships. Inasmuch as the initial temperature, T_1, greatly affects the final temperature, T_2, the following equation is usually used in these calculations:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

The compression ratio, V_1/V_2 also affects the final temperature T_2 at various temperatures, T_1, as shown in Fig. 3, which expresses the temperature-volume relationships for the various initial temperatures T_1.

Considering the compression pressure-temperature relationships as shown in Fig. 4, for the various pressures at several values for the initial temperature, T_1, the value of n given as 1.35 is about the best that can be obtained for Diesel engines. The assumed suction pressure of 14.7 lb. per sq. in. abs. or zero gauge is not usually obtained.

It is convenient for reference to have a chart showing the final temperatures in °F. and the final pressures in lb. per sq. in. plotted with the various compression ratios. These are given in Fig. 5. The dotted line shows the pressures if the initial pressure P_1 is 14. lb. per sq. in. abs., and the polytropic exponent is $n = 1.35$.

The solid lines indicate variations of temperatures in °F. with initial temperatures varying from 260°F. to 30°F., lines 1 to 6. When estimating the compression temperatures for various compression ratios R_c from 12:1 to 17:1, and for the different values for n, with the initial temperatures assumed to be 63°F., the final compression temperature T_2 will then depend upon the value of n and the compression ratio R_c. The final temperature T_2 at different values of n are given in the chart, Fig. 6.

These charts afford a ready reference and cover virtually all requirements for practical Diesel work.

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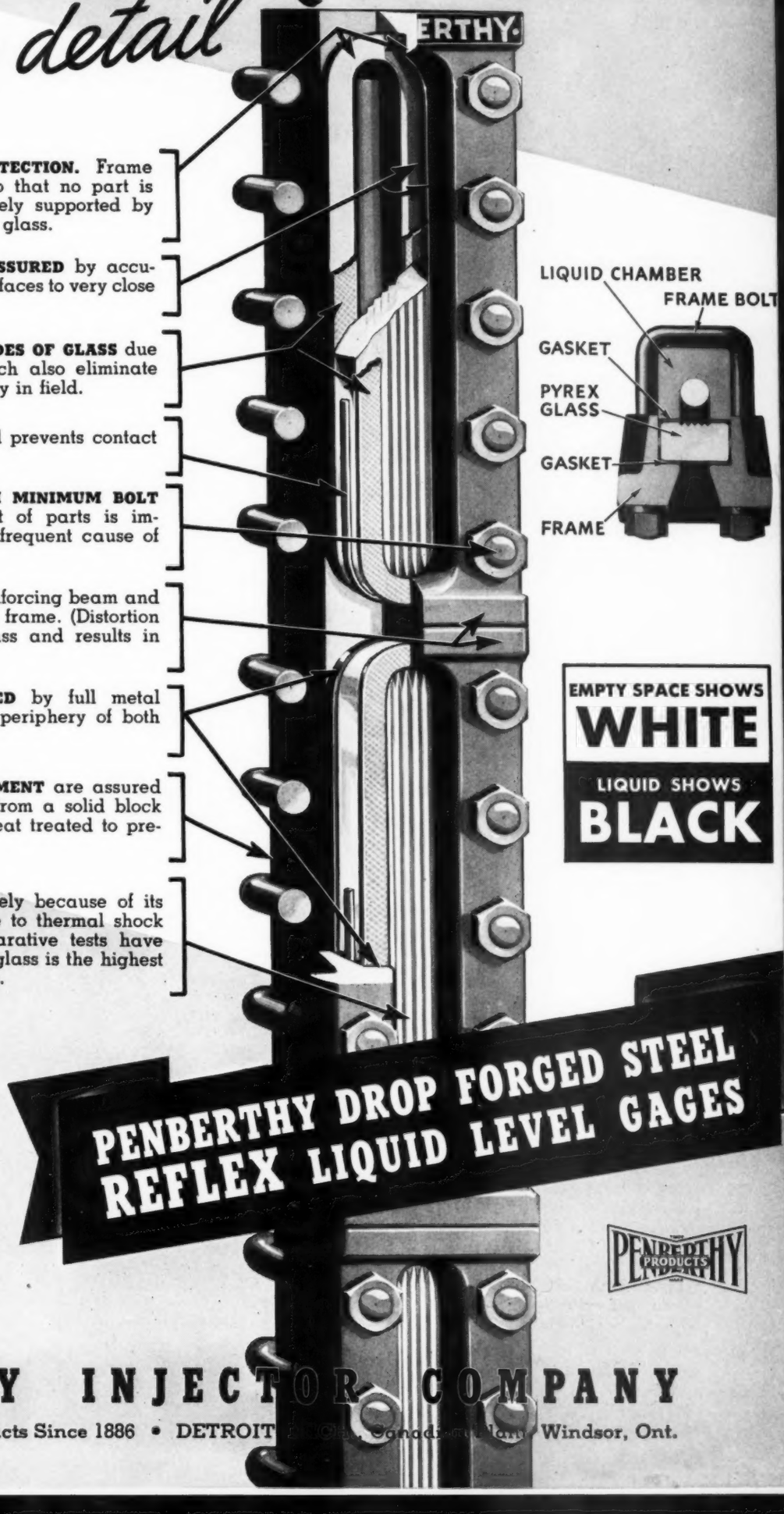

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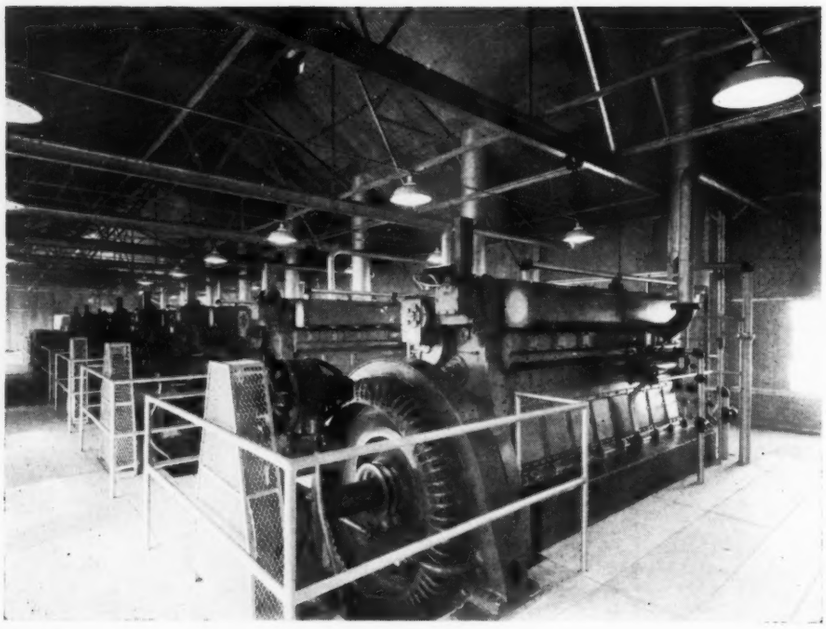

These 400-hp., 8-cylinder, 4-cycle full-Diesel convertible engines are direct-connected to 312½-kva., 4160-v., 3-phase generators (250 kw. rating at 80 percent power factor).

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by

W. C. Lane

Consulting Electrical Engineer

Operating Data on Electrical Oil-Well Pumping

☆ Plant in Fitts Pool, Oklahoma, has been in service four years—Static condensers installed to improve power factor

THE Fitts pool, Pontotoc County, Oklahoma, was opened by E. H. Moore and associates in July, 1933. The first production found was in the Hunton lime but subsequently several other zones were found to have commercial possibilities. The depth of the wells completed in the different zones varies from 1800 ft. for Gilcrease sand producers to 4500 ft. for those producing from the Wilcox. The development of the field was rapid but orderly. Ten-acre spacing was the rule and by the end of 1936 approximately 600 of the 950 wells ultimately completed as producers had been drilled.

Fortunately for the discoverers of the pool, the area had not been regarded by operators in general as particularly promising. This error in judgment made it possible for E. H. Moore and those associated with him in the pioneer project to obtain control of a large block of acreage. As a result it was necessary for E. H. Moore, Inc., to inaugurate a more extensive drilling campaign than any other single operator in the field. In 1936 it was thought that it would be necessary for the company to drill only 150 wells in order to develop its leases fully but by reason of subsequent field extensions and the discovery of production in zones previously believed to be barren, 225 wells were completed as producers. The distribution of the wells among the different zones is as follows: Gilcrease 9, Cromwell 21, Hunton 61, Bromide 112, Wilcox 21, and Oil Creek, 1.

Early in the life of the field it was evident that a water problem existed. Salt water appeared in several of the producing zones in a few wells and there was much speculation as to the source of the water and the future extent. By the summer of 1936 the natural decline in the production of some of the older wells and the water problem indicated the time had arrived when definite steps should be taken to provide lifting equipment if loss of production was to be avoided. Gas from a compressor station was available to "kick-off" some of the more sluggish wells on the Moore property but this could be used only as a temporary expedient.

Experience has demonstrated that every new pool presents a slightly different lifting problem. Being fully cognizant of this, the Moore organization decided to employ an engineer to make an extensive study of the pumping problem at Fitts and to submit a report on the subject. The recommendations finally submitted were based on a careful analysis of all the commonly accepted lifting methods used in the industry. The decision to recommend the use of electric motors was based on factual data obtained from a number of reliable sources.

As this article is intended to be primarily an abstract record of the operation of an electric installation rather than an outline of the reasons for using electricity on the specific project, the reasons back of the engineer's recommendations will not be discussed here. It is not out of place, however, to point out that on a property having wells whose depths and potentials differ so widely, electric motors offer a flexibility of operation that is difficult to duplicate.

Initial Power Plant Equipment

The initial installation included three 400-hp., 400-r.p.m., 11½-in. by 13½-in., 8-cylinder, 4-cycle, full-Diesel convertible engines equipped to operate on gas. The engines are connected to 312½-kva., 4160-v., 3-phase, 60-cycle generators normally rated at 250 kw. at an 80 percent power factor.

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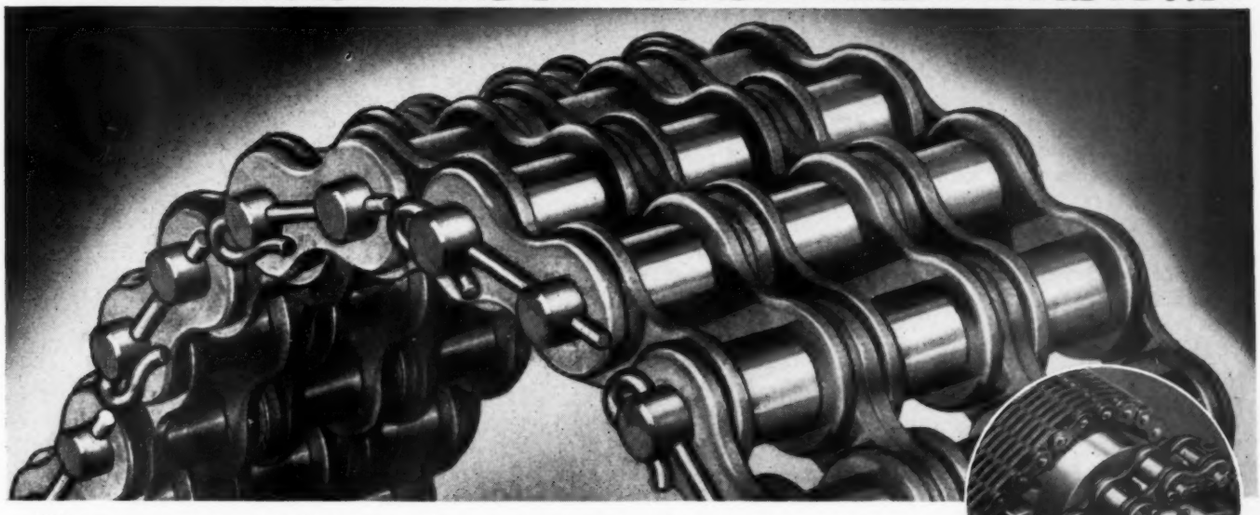

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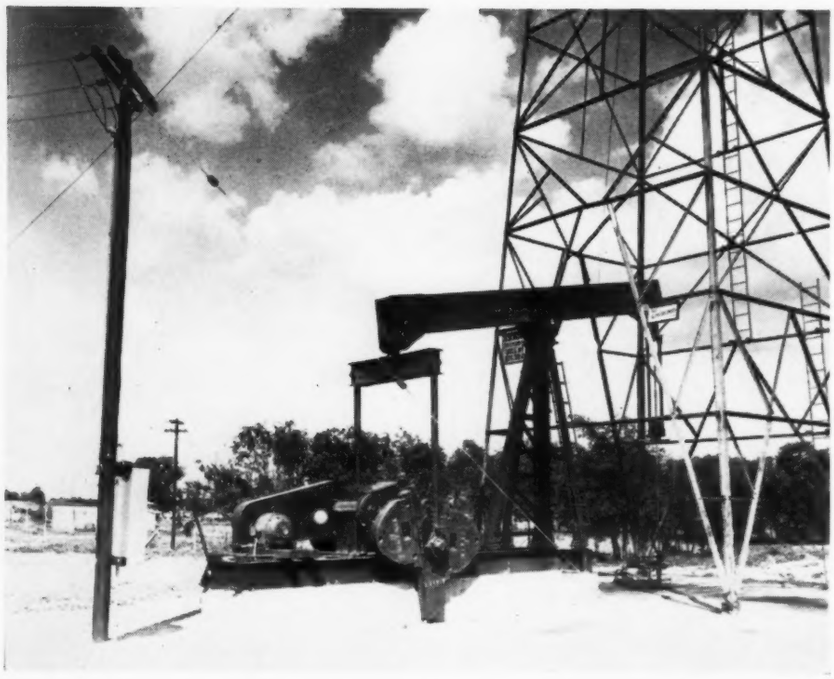

One of the 158 wells pumped by electric power on E. H. Moore, Inc., Fitts pool properties

The exciters are shunt wound 7½-kw., 120-v., 1750 r.p.m. and are driven with V-belts from sheaves attached to an extension of the shaft of each main generator. Each unit has an individual control panel equipped with manually operated oil circuit breaker, voltage regulator, and the necessary indicating meters. A switch for the governor motor of the companion engine makes it possible for an operator to synchronize an oncoming unit without assistance. No generator field rheostats are used and experience has demonstrated that they are superfluous. Separate feeder panels are provided for controlling the outgoing power lines, each line being protected by a relay-operated oil circuit breaker and a watthour meter is provided to record the energy output.

Equipment Added

On January 1, 1937, when the plant was put in operation, six wells were equipped for pumping. At the end of seven months the average load had increased to 615 kw., the maximum hourly demand to 742 kw., and the amount of energy supplied to the field during the seventh month was 280,000 kw-hr. In August, 1937, a fourth unit was installed; four others were added in September. At this time the salt water problem had reached such proportions that it was believed wise to order two additional units. This brought the nominal capacity of the plant to 2500 kw. The coördination of the engine and generator capacities are such, however, that when an engine is fully loaded a generator will be carrying 269 kw. In order to accomplish this it was necessary to increase the power factor of the load to 86 percent, at which time the capacity of the plant was 2690 kw. At the beginning of 1938 the average load was 1168 kw. and the maximum hourly load was 1300 kw. In January, 1941, the output of the plant was 1,099,990 kw-hr., the average continuous load 1489 kw., and the hourly maximum demand 1750 kw. This amount of energy is serving 158 wells.

Plant Investment

The investment in the plant as of March 1, 1937, was $88,000 and it reached a maximum of $289,640.92 soon after the beginning of 1938. Capacitors were installed on the secondaries of the transmission system later in the year of ample capacity to increase the power factor to 86 percent or more. If the sum invested in capacitors is added to the total plant investment, the cost per kw. of plant capacity is $110.50. The figure representing plant cost includes plant site improvements such as a fenced, graded, landscaped lawn, and cement walks.

Inasmuch as increasing the power factor from 65 to 86 percent not only increases the power plant capacity and that of each transformer in the distribution system but also decreases the energy lost in the lines of the transmission system 75 percent, strictly speaking a major portion of this item should be charged against distribution rather than to the plant. If this is done the cost of the plant is approximately $109 per kw. capacity.

Early in 1939 it was believed that more plant capacity had been provided than would be needed. The average load on the wells was lower than had been anticipated, some of the Hunton wells in the east side had flooded out, and others in the west side had dried up, so to speak, so it was becoming unprofitable to produce them. Fortunately the equipment in the plant was chosen with just such an occurrence in mind. The units are comparatively small and each, together with its control panel, is complete in itself so that they may be salvaged one at a time and moved to a new site without excessive cost. One unit was moved to the company's property at Zenith, Kansas, and two were sold for slightly more than 75 percent of their original cost.

Pay-Out of Plant

For those who wish to assume some amortization period and calculate the payout of the plant the following costs are given. As nearly as can be determined the average investment during the first year (1937) was $125,000, the second $289,640.92, and the third $241,863.14, credit being given for $47,777.78 for the three units salvaged. The rate of interest paid for the capital invested is 4 percent.

Cost of Energy

It is the writer's belief that in determining the cost of energy only real items of expense should be included. Not infrequently accounting systems involve practices that cause costs to be substantially higher than they really are and as a result busy executives have erroneous notions concerning their costs. As a specific illustration a charge is often made for gas for which there is absolutely no market. In other cases the plant is charged a price higher than that received for the same product when it is sold to outsiders. Perhaps the most abused charge is that of overhead expense. It appears to be misleading and unfair to a plant to prorate the item of supervisory expense in proportion to the amount invested in plants rather than in proportion to the amount of time and expense actually spent in supervising different projects controlled by an organization. In the data presented subsequently in this story actual costs are used, unless estimates known to be approximately correct were used to eliminate much useless work.

The Moore leases provide an ample supply of sweet gas for which there is no market. Inasmuch as this gas would

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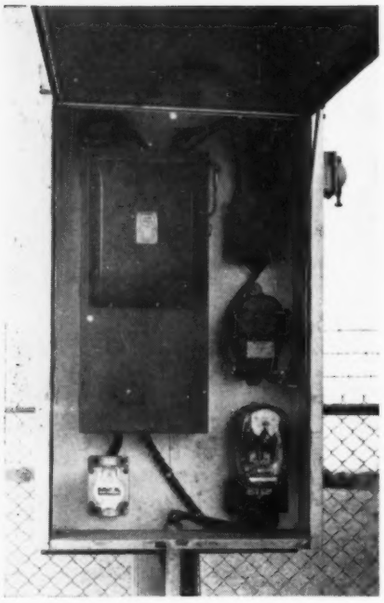

Up-to-date control equipment is provided at every well

be collected, stripped in a neighboring gasoline plant, and returned to the property for disposal regardless of the existence of a power plant, one is not justified in making a charge for it. Water for cooling purposes is obtained from a spring-fed creek that passes through the property. The water is lifted by a motor-driven pump that supplies the field and the additional cost of water for the plant is almost negligible. Clean water that is treated and used in the closed system of the heat exchangers is obtained at 1 cent per bbl. from the water line that supplies the City of Ada.

Cost of Operating Power Plant

The materials used in operating the plant, station output, energy used by the plant auxiliaries, and items of a similar nature susceptible of being appraised are metered or tallied carefully and records maintained from which the costs presented were obtained. Insurance on the equipment was carried for the first three years, then discontinued. As a result of an oversight ad valorem taxes were paid for a time, although in Oklahoma the gross production tax covers all equipment used in the production of oil. As a refund of this item is problematical it is included in the cost. Labor costs include sums paid to men, social security, and unemployment insurance. It includes also a major portion of the salary of the electrical superintendent whose other duties include the supervision of the transmission system and all pumping equipment, directing the company carpenters, painters, and welders, and numerous duties not associated with the power plant. The "overhead" items are so designated by the writer and may be regarded as liberal as very little administrational expense not included under labor is incurred because of the plant. (See Table 1.)

The Fuel Problem

At the present time it appears that an adequate supply of gas will be available for operating the plant for a number of years to come. From the data presented elsewhere it may be seen that the average amount of gas used per kw-hr. supplied to the field during the four years covered by the report was 15 cu. ft. If it had been necessary to buy this gas at, say, 8 cents per M. cu. ft., the cost of energy would have been increased 1.2 mills per kw-hr. This would have increased the average cost for the four years to 4 mills. For the last year it would have been 3.6 mills per kw-hr. Should it ever happen that the supply of gas becomes inadequate and gas cannot be obtained at a reasonable rate, the company can resort to Diesel fuel as the engines are convertible.

Present Conditions

At this time 158 wells are being pumped three of which are equipped with submersible centrifugal pumps. The use of submersible pumps makes it possible to lift large quantities of fluid from Wilcox sand wells and thus produce wells at a profit that otherwise might have to be abandoned soon. In addition to supplying energy for pumping, two clean-out strings of cable tools are operated as needed, water for the field and plant is pumped from the creek, tank batteries and camps are lighted, and miscellaneous service such as operating pick-up pumps is given. Energy for the Fitts Salt Water Disposal System, a coöperative association operated by E. H. Moore, Inc., for members of the system, is supplied by the electric plant.

The present monthly load of more

TABLE I

Materials used and cost of operation of power plant

Year	1937	1938	1939	1940
Energy produced and materials used				
Station output in kw-hr.	4,710,665	10,283,995	9,657,515	11,765,637
Energy delivered to field, kw-hr.	4,120,000	9,505,496	8,805,070	10,515,900
Average station load, kw.	538	1,174	1,102	1,339
Average field load, kw.	647	1,085	1,005	1,201
Maximum station demand, 1-hr. interval.	1,580	1,622	1,715	1,785
Maximum field demand, 1-hr. interval.	1,211	1,527	1,530	1,602
Raw water used, bbl.	121,255	130,600	108,005	144,950
Ada water used, bbl.	4,414	1,795	1,586	1,856
Salt water used in treating water, bbl.	9,410	3,500	3,500	2,900
Lubricating oil used, gal.	5,930	8,582	6,252	7,582
Gas used by plant, cu. ft.	78,422,000	142,965,000	123,317,000	162,541,000
Materials used per kw-hr. generated				
Gas, cu. ft. per kw-hr.	16.8	13.9	13.0	13.8
Gas supplied to field, cu. ft. per kw-hr.	18.9	15.0	14.1	15.1
Raw water, bbl. per kw-hr. generated.	0.02570	0.01270	0.01120	0.01232
Make-up water, bbl. per kw-hr. generated.	0.00094	0.000174	0.000164	0.000159
Salt, per 1000 gal. treated.	50.7	46.4	52.7	31.2
Lubricating oil, gal. per kw-hr. output.	0.001258	0.000861	0.000645	0.000644
Cost of operation of plant				
Labor, Social Security and state insuran e	$ 7,512.74	$10,551.96	$13,117.24	$10,016.55
Lubricating oil.	3,238.56	3,902.89	2,361.40	3,791.00
Raw water @ ½ cent per bbl.	606.28	653.00	540.08	724.75
Ada water @ 1 cent per bbl.	44.14	17.95	15.86	18.56
Salt and other chemicals.	94.10	35.00	35.00	142.72
Repairs and miscellaneous items.	158.19	1,134.07	1,931.07	*8,555.74
Plant and equipment insurance.	2,520.63	2,520.63	2,520.63	244.00
Taxes (paid erroneously).	880.00	2,896.41	1,900.00	132.58
Overhead expense (assumed).	2,500.00	2,500.00	2,500.00	2,500.00
Total.	$17,554.64	$24,211,91	$24,921.28	$26,125.90
Cost of energy produced				
Cost of energy generated per kw-hr.	3.7 mills	2.4 mills	2.6 mills	2.2 mills
Cost of energy supplied to field.	4.2 mills	2.5 mills	2.8 mills	2.4 mills
Average cost of energy generated for four years.	2.5 mills			
Average cost of energy supplied to field, 4 years.	2.8 mills			

*Note: It may be seen that the cost of repairs increased sharply during the fourth year. This was due principally to corrosion difficulties discovered in the heat exchangers that made it necessary to replace many of the tubes. As remedial measures were taken to prevent the recurrence of this trouble it will probably not appear again or at least not so soon.

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1" splined rings provide 25% more absorption surface than 1" smooth rings.

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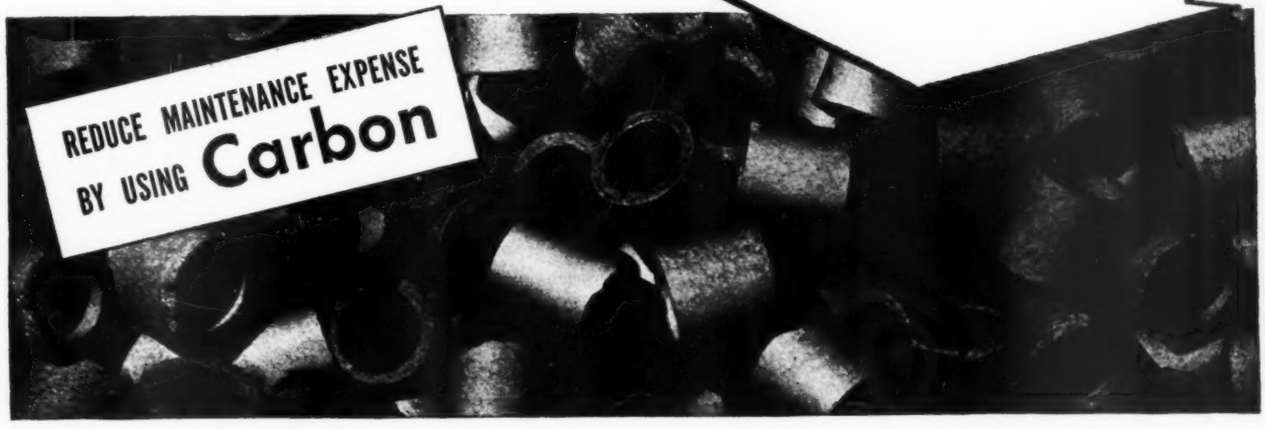

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than 1,000,000 kw-hr. will probably not decrease much in the near future. As wells become unprofitable to produce and are plugged, the demand for energy increases on others so the load tends to remain about constant. It is necessary to run six of the seven units in the plant continuously and the seventh must be run part-time. Obviously the load factor is very high. The power factor is above 90 percent all the time so the line losses are lower than one finds in a field where no corrective equipment is provided.

The reliability of static condensers for power factor correction has been established beyond question. Approximately four years ago, 830 kva. (480 volt) in capacitors was distributed over the property at a cost of $9.55 per kva. installed. Currently, 780 kva. of the original capacity is in service. The loss by lightning and other causes has amounted to approximately 1.5 percent per year. As the item of line loss alone, i.e., energy loss, is inversely proportional to the square of the power factor, it may be seen that the energy saved will soon pay for the losses in capacitors. This is usually considered to be a minor matter and unworthy of consideration, the other advantages to be gained being the only ones mentioned.

It appears obvious that low cost energy for pumping and the reduction in field labor made possible by the use of electricity will prolong the profitable life of every well served. The Moore organization has in use a number of time switches that make it possible to operate wells on any desired schedule. These, in combination with high slip motors that have a high starting torque, enable a switcher to supervise a large number of wells. If it should happen that the load decreases to such an extent that all the units in the power plant are not needed to carry the load, no difficulty will be experienced in disposing of the excess equipment. Scarcely a month has passed in which some one does not inquire at the office of the company concerning the possibility of purchasing a unit.

P 094.6

Determining Effective Pull and Power Transmitted by Belt Drives

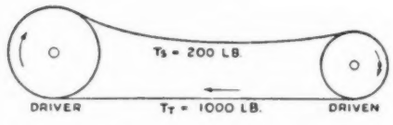
by

W. F. Schaphorst

THE accompanying sketch shows a common horizontal oil plant belt drive in which there is a pull of 1000 lb. on the tight side, and 200 lb. on the slack side.

The so-called "effective pull" is the tension on the slack side subtracted from the tension on the tight side, or, 1000 lb. — 200 lb., which is equal to 800 lb.

It is plain that if the pull were 1000 lb. on both sides no power would be transmitted because the drive would then be in "perfect balance": 1000 — 1000 = 0. In other words, there must be a "difference" in tension. If there is no difference there will be no motion, and without motion power transmission is impossible. The "difference" is what is commonly termed "effective pull."



Now, knowing the effective pull, it becomes easy to determine the power transmitted by the belt. This is the rule: Multiply the effective pull in pounds by the velocity of the belt in feet per minute and divide by 33,000. The result is the horsepower transmitted.

When making estimates for single belts, engineers generally allow approximately 35 lb. per in. of width, and 50 lb. for double belts. For the tension on the tight side for single belts 70 lb. per in. of width is commonly allowed and 110 lb. is the figure used for double belts.

NINTH ANNIVERSARY OF INHIBITED ACIDIZING

The present highly developed Chemical Service for oil and gas wells had its inception nine years ago when the INHIBITED Acidizing technique was announced by The Dow Chemical Company, parent company of Dowell Incorporated. Because this method protected metal well equipment from corrosion, yet permitted the acid to accomplish the desired results in the formation, INHIBITED Acidizing was widely acclaimed and accepted by the industry. The service did not stop there. Dowell was to play a much larger part in the exciting drama of oil production.

The widespread acceptance of the INHIBITED Acidizing technique has made it possible for Dowell to expand its facilities until chemical research and engineering now serve the entire field of oil and gas production. So important has this service become that INHIBITED Acidizing is considered an essential and integral part of production procedure.

That the benefits resulting from the development of INHIBITED Acidizing have not been one sided, that producers have shared in its advantages, is witnessed by a lengthy and interesting parade of accomplishments. Dowell has treated tens of thousands of wells; recovery has been stepped up; millions of dollars in extra profits have been the producers' reward. More, Dowell service can now be applied to an ever-widening variety of problems facing producers.

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Survey of Odorizing Practice in Gas Transmission

PETROLEUM ENGINEER Exclusive Feature

☆ Odorization now generally recognized as valuable aid in reducing "unaccounted-for losses"

by Roy W. Parker

Oklahoma Natural Gas Company

ODORIZING is interpreted as the practice of continuously injecting an odorant, thereby imparting a distinctive odor to *all* gas distributed *all* the time. The italics are to stress that odorizing, thus defined, is to be differentiated from the practice of stenching, or intermittent injection. The latter idea was born many years ago but it has been only in the last ten years that the continuous odorization phase of gas distribution has been given serious consideration, resulting in the more or less general development and acceptance of the practice. A review of the many interesting and informative articles written as odorization developed is indicative of the rapid progress made since engineering principles were first applied. It is apparent from recent surveys that those companies who now odorize are endeavoring to further perfect their equipment and methods and those not odorizing are becoming more and more interested as the scope and results are brought to their attention.

A recent survey of gas odorization practices by questionnaire is interesting and indicates the scope and practices of odorization[1]. These questionnaires were sent to all natural gas companies listed in the 1938 Brown's Directory as having an average daily delivery of more than 3000 M. cu. ft. per day. One hundred and twenty-seven replies were received, some of which were consolidated reports covering several divisions. Tables 1, 2, and 3 show the number of reporting companies, grouped under various headings in relation to odorization, the average daily deliveries for each classification and the recapitulation. An analysis of the three tables might be summarized as follows:

(a) Seventy percent of the gas sold by distributing companies is odorized as indicated by 65 percent of the companies reporting.

(b) All reporting companies, even those odorizing because of state requirements, agree, with one exception, that odorization is essential and the expense is justified.

ROY W. PARKER

has been in the employ of the Oklahoma Natural Gas Company for 14 years, one year having been spent in the measurement department, one year in the meter repair department, four years as assistant chemist, four years as chief chemist, and the last five years as industrial sales engineer — Prior to his affiliation with Oklahoma Natural he had been employed in the refining department of The Texas Company, from 1923 to 1926 — He is a graduate of Southeastern State College.

(c) The trend is to trunk-line installations rather than district odorizers, except where local conditions prevent.

(d) Although there are variable factors of odorant volatility over a wide range of temperature and pressure variations, reasonable accuracy can be expected with present equipment.

It is possible that the desire to odorize continuously began several years prior to 1930, the year the trend became more general. Before this date there did not seem to be a satisfactory odorizing medium. Warning agents could be obtained but as the requirements were so rigid, none proved suitable. The natural gas industry was expanding rapidly and much of this expansion involved transmitting natural gas to cities that, formerly were served by manufactured gas, which did have a distinct odor and it was desirable to maintain this condition. About this time two odorants were found to meet all the requirements necessary for proper odorization. These requirements are: (1) harmless and non-toxic; (2) inexpensive; (3) non-fatiguing to sense of smell; (4) non-corrosive and insoluble in water; (5) no noticeable product of combustion; (6) penetrating odors similar to that of city gas, and (7) stable in transportation. The records show that three warning agents are in general use, the first two more widely than the third:

1. Calodorant—A complex mixture of hydrocarbons and an organic sulphur compound, manufactured by the Standard Oil Company of California. The sulphur occurs in the form of benzene ring or other complex staple compounds.
2. Pentalarm—Composed principally amyl-mercaptan, manufactured by the Sharples Solvent Corporation.
3. Ethyl mercaptan.

Opinons differ as to the merits of Calodorant and Pentalarm, but reports indicate that both are proving satisfactory for the same purpose. The average concentration is approximately 2 gal. of Calodorant or 1 lb. of Pentalarm per million cu. ft., which gives a noticeable odor when only 0.2 percent gas is present in air. Reports show that many companies increase the odorant concentration during the winter and other companies make an increase in the summer. The increases average about 50 percent of the established normal injection rates. The concentrations given above for the two trademarked odorants seem to be the minimum concentrations advisable for maximum safety. Tests have proved that when lower injection rates are tried the effectiveness is reduced in approximately the same ratio. At the above rates the cost is less than one dollar per million cu. ft. treated.

After the development of satisfactory odorizing mediums, those companies wishing to odorize were then confronted with the problem of de-

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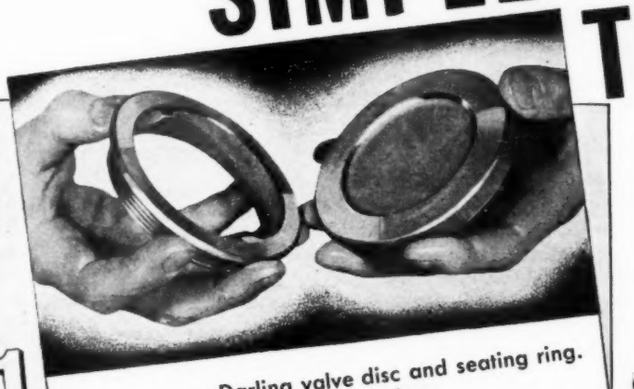

1 Take any new Darling valve disc and seating ring. Or, valve disc and tapered wedge.

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3 Pour water into the "cup". Though gravity alone holds the ring to the disc, not a drop of water escapes!

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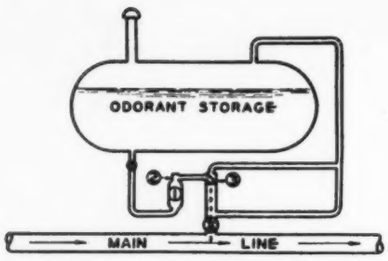

Fig. 1. Liquid injection odorizer, lubricator type

termining what equipment to use and of devising proper methods of operation. As with most mechanical equipment, improvements in design have been developed from time to time by various engineering departments. Because of this engineering interest the equipment and practices have progressed until this phase of gas distribution is no longer experimental. Manufacturers of odorizing equipment and company engineers have done an excellent job of designing and building equipment capable of performing a given odorizing operation. There is often, however, the question of economical operation depending upon the design of any given gas distribution system. When the industrial load is negligible, transmission line odorization is adaptable. If, however, large volumes of gas are being delivered to industrial consumers where odorized gas is not necessary, then it probably would be economical to install smaller individual odorizers at several points in the distribution system. The apparatus now in general use can be divided into two groups: (1) equipment that injects the fluid directly into the gas stream, and (2) the bypass or vaporizing type where the vapors are carried away (picked-up) by the gas flow. For the purpose of a review several types of the two classifications will be shown and discussed.

The first group, or the direct-injection type, can be sub-divided into three representative types, namely: lubricator, differential controlled, and pressure-differential controlled.

Odorization in the beginning was principally confined to certain districts and the lubricator type was popular. Obviously, the homemade equipment generally in use was somewhat crude, but in later years lubricator-type equipment, as well as the other groups, has taken on a more streamlined appearance, as well as exhibiting more exacting operating behavior.

In Fig. 1 is shown[2] a lubricator type recently designed by Bruce MacCannon. It has an unusual feed control consisting of a ceramic filter through which the odorant percolates. This gives better control of injection and is particularly adaptable to small, steady gas flows. The accuracy of this type odorizer is affected if gas flows fluctuate over a wide range.

Figs. 2 and 3 show two types of differential controlled injectors. The injector in Fig. 2 incorporates a varying liquid head and the one in Fig. 3 operates with a constant head. The governing factors of accurate odorization with these types is the calibration of the liquid orifice located at points (3) and (4) in ratio to the main line orifice area. Both types, too, are dependent upon a fairly constant differential pressure for satisfactory odorization. The effect of pressure and temperature fluctuations on the rate of absorption in these proportional types must be considered.

The third type of injector is the pressure-differential controlled unit. Considerable study and work has been devoted to this type of equipment in recent months, especially on the West Coast. It is reported[3] by one company that the particular need, because of pressure variations from 100 to 300 lb. per sq. in. and volumes of 5,000,000 to 200,000,000 cu. ft. per day, necessitated equipment that was not readily available. Confronted with this odorization problem and with a basic

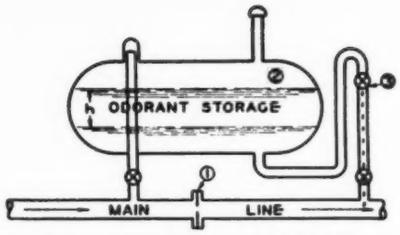

Fig. 2. Liquid injection odorizer, differential controlled type with varying liquid head

knowledge of odorizing equipment and technique, a rather elaborate and precise unit was built. To assure constant calibration governing the odorant-gas ratio, this installation employs several unique hook-ups that render it fully automatic and accurate. Because it is different from the conventional types, a brief description of the equipment and its operation is warranted. Fig. 4 is a diagrammatic sketch of this installation.

In selecting a means of controlling definite injection rates for the variable conditions, the integrating orifice gauge was decided upon. With this device the problem became one of supplying a method of operating a positive displacement device to deliver the liquid odorant into the pipe line. Precisely machined slide valves were made and

TABLE I

Questionnaire Summary by States

State	*No. of companies reporting*	*Odorizing; Expect to odor.; pur. odor. gas*	*Sour gas*	*Odorize occasionally; do not odorize; wholesalers producers*
Alabama	2	1		1
Arizona	2	1	1	
Arkansas	2	2		
California	9	9		
Colorado	3	1		2
District of Columbia	1	1		
Delaware	1			1
Georgia	3	3		
Illinois	6	5		1
Indiana	2	2		
Iowa	2	2		
Kansas	5	1	1	3
Kentucky	1			1
Louisiana	4	4		
Michigan	6	6		
Minnesota	3	3		
Mississippi	1	1		
Missouri	6	4		2
Montana	2	2		
Nebraska	4	2		2
New Mexico	2	1	1	
New York	7	5		2
Ohio	5			5
Oklahoma	6	1		5
Pennsylvania	11	3		8
South Dakota	1	1		
Tennessee	2	1		1
Texas	17	16	1	
West Virginia	5			5
Wyoming	1	1		
Canada	5	2	1	2
	127	81	5	41

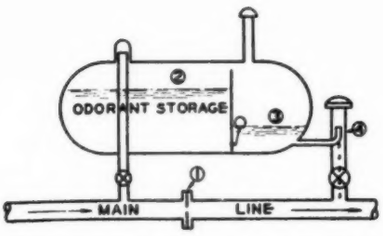

Fig. 3. Liquid injection odorizer, differential controlled type with constant liquid head

used as the displacement devices. The sequence of operation is as follows: Gas is measured through an orifice meter and recorded on an integrating orifice meter, equipped with an integrator counter or totalizer, to the shaft of which is attached a cam. This cam operates a mercoid electric switch that controls the injection valve drive meter. When the injection valve has completed one revolution (during which time a definite amount of liquid is released), a second mercoid or limit switch on the speed reduction unit, breaks the motor circuit. The selected gas-line orifice size is for maximum flow so a tandem orifice gauge is necessary for low flows. The set-up consists of a 500-lb., 50-in. meter and a 500-lb. 2.5-in. meter. The tandem arrangement is of the standard type, except that each gauge or meter has a separate line. Otherwise, the low-range gauge would bypass the higher one on high differentials. The integrating cams are so constructed that the 50-in. gauge begins operating when the 2.5-in. gauge has reached its limit. Each gauge is fitted with a totalizer contact that operates its respective valve. The displacement is 0.200 gal. for the 2.5-in. gauge and 0.900 gal. for the 50-in. One-fourth hp. motors are used in conjunction with 1500:1 speed-reduction units to drive the injection valves. This unit is capable of maintaining the concentration to within 5 percent of that desired.

The second group, or bypass type, also offers a number of designs that are fundamentally similar. That is, a portion of the gas is bypassed through the odorizer where it contacts the odorant and delivers this vapor to the main gas flow. This group can be subdivided into the diffusion type, shown by Fig. 5; the wick type, shown by Fig. 6; and the liquid seal type, shown by Fig. 7. The direction of gas flow and general arrangements, as indicated in these diagrammatic sketches, are self explanatory. In connection with the concentration adjustment of this type apparatus, the reader is referred to an article by T. S. Whitis[4]. The rate of evaporation in this type equipment is also materially affected by fluctuating temperatures and pressures; therefore, consideration should be given these factors when using this apparatus.

These two groups of smaller odorizers, three of the injection type and three of the bypass type, are identified by their simplicity of construction and operation. Although their accuracy is questionable under certain operating variables, these types do serve a definite need on many gas systems.

Recently, the bypass-temperature controlled types have received considerable attention and improved equipment is now available. These recent installations have been of both the con-

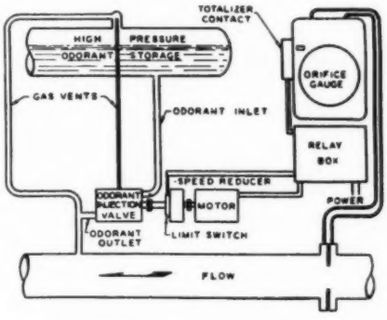

Fig. 4. Pressure-differential controlled injector

tact-diffusion type and the bypass-wick design. It is reported[5] that one company has designed and put in operation several temperature-controlled bypass units that have proved very satisfactory during several months' operation under all existing conditions.

The Lone Star Gas Company[6] odorizes extensively and by reason of the high ratio of domestic deliveries to industrial consumption, it was economical to install large high-pressure units on various trunk lines. The unit developed for this purpose is of the bypass-wick type. Multiple flannel wicks are assembled on a metal frame and this wick-filled cartridge is slipped into the saturator. The report indicates a slight variation in odorant concentration during variable conditions, but the design and method of operation make this negligible. To further facilitate vapor injection accuracy a temperature control installation supplements the odorizer proper. A thermostatically controlled steam-generating unit supplies steam to a jacket placed around the saturator. This controlled temperature minimizes the inaccuracy that would occur with varying temperatures.

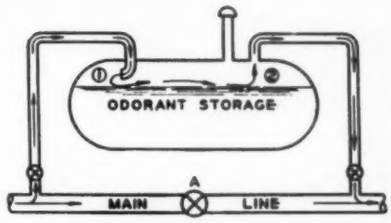

Fig. 5. Bypass odorizer, simple diffusion type

When the injection of liquid odorant into the gas stream became an odorizing rather than a stenching problem, it became apparent that liquid rates must be controlled and some means devised for determining the accuracy of odorant concentration. The importance of this knowledge is apparent, as over-odorizing is uneconomical and under-odorizing might defeat the purpose for which the operation is intended, namely, customer safety and reduction of leakage.

There are two general test methods used: (1) colorimetric and (2) the

TABLE 2

Recapitulation of Gas Companies Reporting

Number		*Average M. cu. ft. per day*	*Percent of total*
74	Odorizing	1,517,000	69.30
2	Expect to odorize soon	7,000	0.32
5	Purchase odorized gas	34,000	1.55
5	Sour gas	39,000	1.78
1	Mixed gas	50,000	2.28
5	Odorize occasionally	147,000	6.72
23	Do not odorize	395,000	18.05
12	Wholesalers and producers		
127		2,189,000	100.00
122	U. S. A. companies	2,151,000	98.3
5	Canadian companies	38,000	1.7
	Total for year	798,985,000 M. cu. ft.	

NOTE: On reports that did not show gas send-out the amount shown in the 1938 Brown's Directory was used. When no figure was shown in Brown's the amount was estimated on the basis of 300 cu. ft. per day per service. Sales of producers and wholesalers were purposely omitted.

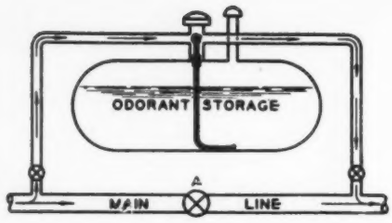

Fig. 6. Bypass odorizer, wick type

calibration or measurement of liquid or bypass gas volumes.

The colorimetric method[7] has recently received considerable attention from chemists in an effort to produce positive visual evidence of exact concentrations. The method was developed in the laboratory and resulted in the adoption of the copper oleate method, inasmuch as mercaptans react with copper soaps. In this method a copper soap is prepared by adding copper nitrate to a solution of cocoanut-base soap. This preparation gives the test filter pieces a bright blue color. When gas containing the odorant is passed through these test filters and the filters then exposed to light, the contacted portion changes to a permanent brown color. The color shade of this test filter is then compared to several standard pieces through which a known amount of odorant has passed, thus determining the definite concentration of odorrant in the gas.

The calibrated volumetric method employs the basic physical laws of gas and liquid measurements correlated with physical properties of the odorizing medium. Many of the injection types use calibrated odorant orifices to procure a calculated volume of liquid injection. Others have sight feeds of known volume from which rates can be determined by timing. The pressure-differential controlled unit has injectors of known liquid volumes operating on a time cycle, the length of which depends on the volume of gas being delivered. As mentioned previously and indicated elsewhere[4], the accurate adjustment of the bypass type is based upon the application of a more or less empirical formula.

In conclusion, it can be said that although most odorizing units are of a similar pattern, there has recently been a definite improvement in odorizing equipment and technique. The statistical data previously mentioned in this article is convincing evidence of the scope and opinions of this phase of gas distribution. This fact alone indicates further study and engineering interest will continue in an effort toward even more improved types and more exacting knowledge of operation.

In closing, the author wishes to express his gratitude to H. G. Caldon, Industrial Fuel Supply Company; C. F. Briscoe, Southern California Gas Company; H. F. Haldeman, Papico Company; W. A. Green, Arkansas Power and Light Company; E. L. Henderson, United Gas Corporation; C. E. Gill, Sharples Solvent Company, and Edward Rolle. Standard Oil Company of California, for their interest and assistance in the preparation of this article.

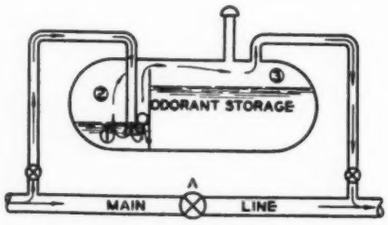

Fig. 7. Bypass odorizer, liquid seal type

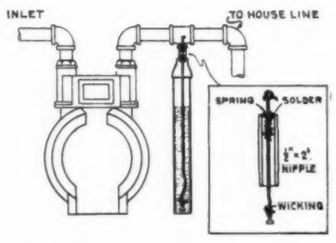

Fig. 8. Wick-type odorizer for domestic service

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[1]"Survey of Gas Odorization Practice," by H. G. Caldon, *Gas Age*, Sept. 14, 1939.

[2, 3]"Use of Integrating Orifice Gages in the Odorization of Gas in Pipe Line Systems," by C. F. Briscoe and H. G. Caldon, *Gas*, April, 1938.

[4]"By-Pass Odorizers—Their Direct and Accurate Adjustment," by T. S. Whitis, *Gas*, Jan., 1938.

[5]"Odorization of Natural Gas and Its Advantages," by W. A. Green, *Gas Age*, March 31, 1938.

[6]"Introducing Odorants Into High-Pressure Gas Lines," by T. S. Bacon, *Gas Age*, June 20, 1940.

[7]"Testing Natural Gas Odorants for Mercaptans," by O. K. Smith and G. T. Williams, *Gas Age*, Aug. 3, 1939.

TABLE 3

Questionnaire Recapitulation

Average odorization send-out		
with Calodorant	1,181,000	M. cu. ft. per day
with Pentalarm	247,000	M. cu. ft. per day
with other odorants	89,000	M. cu. ft. per day
Average concentration		
Calodorant	2.01	gal. per MM
Pentalarm	1.13	lb. per MM
Pressure		
Average maximum	147	lb. per sq. in. gauge
Overall average	77	lb. per sq. in. gauge
Temperature		
Gas		
Average maximum		78°F.
Average minimum		40°F.
Odorizer		
Average maximum		90°F.
Average minimum		25°F.

Type Odorizers Used	*No.*	*Avg. M. cu. ft. gas odorized per day*
Direct injection		
Drip type	306	131,700
Drip type with differential control	49	121,000
Drip type with differential control and constant liquid head	117	872,500
Meter operated pump type	1	1,500
Pressure and differential controlled type	4	86,000
Bypass and wick odorizers		
Individual house service odorizer	3,979	1,800
Simple bypass and wick types	239	198,000
Bypass constant level	5	8,600
Bypass with constant level and constant temperature	6	68,700
Bypass with liquid seal and overflow	13	27,600

Is Your Trend to District Odorizers or Trunk Line?

District	20
Trunk line	43

	Yes	*No*	*No answer*
Do the results justify the expense?	69	1	4
Benefits obtained in:			
Reducing unaccounted for losses	37	12	25
Customer protection and safety	61	0	13

P 537.9

Electrical Models as an Aid in Visualizing Flow in Condensate Reservoirs

PETROLEUM ENGINEER Exclusive Feature

☆ Example is given in which recovery of wet gas from parallel sands is estimated

by William Hurst

Research Engineer, Humble Oil and Refining Company

THE numerous discoveries in recent years of gas-condensate fields have been responsible for the considerable emphasis given to the construction and utilization of cycling plants. Likewise, added incentive has been given to the study of vapor phase behavior at high pressures, especially with reference to the optimum conditions for the removal of condensate from the gas. It is significant to add in this respect that although the advent of high-pressure cycling is fairly new, a considerable amount of research work has already been accomplished in this field. Furthermore, the large investment in the reservoir proper has made it essential that study be given to the problem of locating wells with respect to the configuration of the producing sand as it affects the ultimate recovery of wet gas in cycling, and it is this aspect of the problem that is discussed in this article.

Electrical Models

The means employed for the determination of the mechanics involved in recovery of wet gas in a cycling operation were electrical models in which the reservoir conditions were simulated. The basis for the analogy by which an interpretation of electrical data may be made to serve in a study of gas fields is that the flow of gas in the formation expressed by D'Arcy's law is analogous to the flow of electricity expressed by Ohm's law. D'Arcy's law states that the velocity of gas flow is proportional to the pressure drop per unit length along the line of flow, and Ohm's law expresses the current as directly proportional to the voltage drop per unit of length. In brief, the pressure function distribution in the gas sand and the voltage distribution in the model are identical, if the shape of the sand formation and the location of the wells are reproducible in the model.

Heretofore, one of the uses for electrical models has been its adaptability for the study of two-dimensional gas cycling problems. In this application, the formations have been visualized as the ideal case of gas flow in a sand of uniform thickness and permeability with the areas of the wave-fronts swept out by dry gas sharply defined from the wet gas. In actual practice, however, it is not to be expected that the two-dimensional flow will always be met, but rather the variations in sand thickness and permeability will induce a vertical as well as horizontal distortion of the wave-fronts, giving rise to a three-dimensional flow problem. The possibilities of three-dimensional electrical model studies, employing a dimensional relationship in correcting for the variations in permeability, are also discussed in this article.

WILLIAM HURST

received his early education in the public schools of Boston, Massachusetts—Entered the Massachusetts Institute of Technology in 1924 and received the B.S. degree in chemical engineering in 1928—Graduated from the School of Chemical Engineering Practice, M.I.T., in 1929 with the degree of M.S.—Is now employed by the Humble Oil and Refining Company as research engineer in production and the hydrodynamics of fluid flow in reservoirs—Member of the American Physical Society, Regional A.P.I., and is a registered professional engineer.

Two Methods

Two methods are available to the engineer for model study: the electrolytic and potentiometric methods. The electrolytic method employs the travel of colored ions in a medium under the influence of a voltage potential, and the colored area swept out with time is representative of the area swept out by the dry gas in producing the wet gas of a condensate field. In the potentiometric method, however, the voltage distribution is obtained experimentally between input and output wells in the model, and from these data the history of the movement of gas along streamlines is traced.

Electrolytic models have been investigated by Wyckoff[1] and Botset[1], Swearingen[2], and others. Wyckoff and Botset employed a cardboard model containing a solution of potassium sulphate and an indicator to represent the field. The flooded area swept out was indicated by the red coloration of the hydroxyl ions in moving from the negative to the positive poles. Swearingen used a solution of zinc ammonium chloride set in agar gel as the field. Glass electrodes containing copper ammonium chloride were used as the input wells, and electrodes of zinc ammonium chloride for the output wells. Upon passing a current through the model, a background was traced out showing the coloration of blue ions.

Potentiometric Method

In a recent paper, Hurst and McCarty[3] showed the application of the potentiometric method for the study of gas cycling problems. The model was constructed of mahogany planking and milled to conform to the shape of the field. A solution of copper sulphate contained within the model represented the formation. The potential distribution was set up in the field by passing

[1] R. D. Wyckoff and H. G. Botset, *Physics* 5, p. 265, 1934.

[2] J. S. Swearingen, *Oil Weekly*, Dec. 25, 1939.

[3] "The Application of Electrical Models to the Study of Recycling Operations in Gas Distillate Fields," by Wm. Hurst and G. M. McCarty, A.P.I. meeting, Shreveport, Louisiana, Feb. 27, 1941.

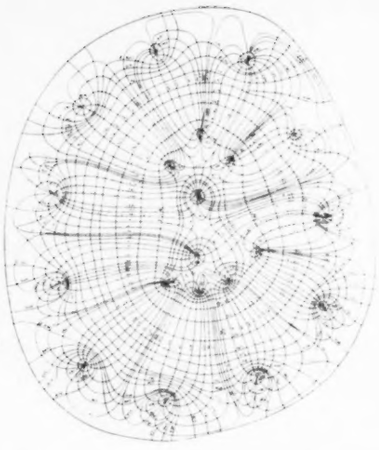


Fig. 1. Potential and streamline distribution for reservoir with 11 input and 9 producing wells

an alternating current between input and output wells, which were copper bus-bars. The mapping was made by moving a prober about the solution in determining a potential contour. The prober was mounted on the T-square of a drafting board, and suspended in the copper solution. The potentials were measured by means of a potentiometer, using a sensitive galvanometer. The areas swept out by the dry gas were calculated from the streamlines as follows:

By expressing the gas velocity as proportional to the potential drop per unit of length along the streamline (D'Arcy's law), and equating this with the distance, $S\psi$, on the curve in the time, t, then:

$$dS\psi = \left|\frac{d\Phi}{dS\psi}\right| dt$$

and

$$dt = \frac{dS\psi}{\left|\frac{d\Phi}{dS\psi}\right|}$$

giving

$$t = \int_0^{S\psi} \frac{dS\psi}{\left|\frac{d\Phi}{dS\psi}\right|} \quad . \quad . \quad . \quad (1)$$

The graphical integration of equation (1) gives the history of travel of a gas particle beginning at an input well and moving over a streamline toward the producing well. A smooth curve drawn through the points on the different streamlines for a given time corresponds to the wave-front swept out by the dry gas at this instant.

The application of the potentiometric method is illustrated in Fig. 1, which shows the potential contours obtained experimentally for a cycling program in which 20 wells are used. These wells are arranged in two groups, one containing 11 periphery wells and the other 9 central wells. The potential, Φ, is between a maximum value of unity or 1.0 and a minimum value of zero. The current distributions between wells of a group are equal. The streamlines are drawn normal to the potential curves and are evaluated for flux, ψ.

In Fig. 2 are shown the calculated areas swept out by the potential distribution of Fig. 1, with the periphery group the input wells. Fig 3 shows the reverse condition with the central group the input wells and the periphery group the producing gas wells.

Comparison of Methods

The writer has employed both the electrolytic and potentiometric methods in electrical model analysis, and it is concluded that each method has its advantages and disadvantages. The electrolytic model is adaptable to showing a wave-front advance in a matter of a few hours, but the results cannot be accepted on a quantitative basis to give the characteristic curves for the instantaneous and overall ratios of wet to total gas production with time, which are important in the determination of the economic life for gas cycling. This is a limitation of the experiments that show a fading-out effect around the boundaries of the colored ions in the model, and introduces a certain amount of ambiguity as to what does constitute the flooded tracts. This phenomenon occurs early in the test and gets worse with time, but whether it is diffusion, the individual mobility of ions, or even the combination of both, it is difficult to say. The potentiometric method offers a quantitative means for studying gas cycling, as attested by a sensitivity of 1 mm. change in potential mapping[3], but to offset this the calculations take time in carrying out the necessary steps of equation (1). The application, however, of a recent instrumental development[4] of a mechanically linked planimeter and differentiator could reduce this time factor considerably, but even so, this method would take a certain amount of time to carry out the necessary calculations.

In the electrolytic model, it is tacitly assumed that for its application to a gas reservoir, the overall pressure drop will necessarily be small. This assumption is essential because the electrolytic model corresponds to a pressure distribution of the first power, whereas in the gas formation the functional relationship is the pressure squared, and the two conditions are compatible only if the overall pressure drop is small. In many cases in gas cycling, however, this approximation should serve fairly well, but when the sand permeability is low or the extent of the field large, this approximation can be in error. Nevertheless, it can be definitely said that the electrolytic method serves as a rapid means for reconnoitering to determine qualitatively the recovery of wet gas in a cycling process.

The potentiometric method is not subject to this limitation. It can apply for any extraneous condition, with the only restriction being that D'Arcy's law must apply in the reservoir. Actually the interpretation of the potentiometric method has been brought to a development whereby the deviation of the gas laws and the variation of the gas viscosities are considered in the calculations of the wave-fronts swept out by the dry gas. This is discussed in detail in the revised form of the earlier paper[3], in which it is shown that the potential distribution in the electric model is proportional to a functional relationship that contains the density of the fluid and the viscosity of the gas as it varies with pressure. This relationship* $f(P)$ is expressed by:

$$f(P) = \int_{P_0 < P_{min.}}^{P} \frac{\rho dP}{\mu} \quad . \quad . \quad . \quad (2)$$

*The derivation of equation (2) was determined from the LaPlace equation $\Delta^2 f = 0$ for the steady state flow of a single phase fluid through a homogeneous sand. An examination of the literature has failed to reveal this relationship for the LaPlace equation, and therefore, this concept must be considered as entirely original. Its value, of course, lies in the fact that the density and viscosity of the fluid flowing can be considered as variables and functions of pressure, which hereto have always been treated as constants for steady state. As a typical illustration, the radial flow of a single phase fluid to a well is expressed as $f(P) - f(P_w) = (q\rho_s/2\pi KH)\ln(r/r_w)$, where the subscript "w" refers to the well, and K the sand permeability relative to one centipoise.

Fig. 2. Areas swept out by dry gas. Injection wells around periphery

[4]"A Contrast Meter for Photographic Papers," by C. A. Morrison, *J.O.S.A.*, 30, July, 1940.

where ρ is the density of the gas, μ its viscosity, and P the pressure.

Equation (2) is determined by integrating the actual density variation and the gas viscosity with pressure; P_0 is an arbitrary lower limit less than the minimum pressure encountered in the reservoir. Thus, the potential distribution in Fig. 1, Φ, is related to equation (2) by:

$$f(P) = f(P_{min.}) + \Phi\,[f(P_{max.}) - f(P_{min.})] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $f(P_{max.})$ corresponds to this function for the injection well with the maximum input pressure, and $f(P_{min.})$ for the producing gas well with the minimum pressure. The difference of these two terms is related to the rate of gas injected by:

$$f(P_{max.}) - f(P_{min.}) = q\rho s/KH\triangle\psi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where q is the daily rate of gas processed, ρ_s is the density of the gas at the measured conditions, K is the permeability of the sand, H is the sand thickness, and $\triangle\psi$ the overall flux difference for the model, which for Fig. 1 is $\triangle\psi = 3.95$. The pressures in the formation are uniquely determined by the assignment of a pressure at one point only, and applying equations (2), (3), and (4) to the experimental data obtained from the electrical mapping of the model. The calculation of the times for the history of gas travel along a streamline is essentially equation (1) with the exception that density is explicitly defined under the integral, but this in turn is established inasmuch as the pressure variation in the formation is now known.

Gas Cycling in Parallel Sands

Both the electrolytic and potentiometric methods are applicable to the study of the simultaneous cycling of gas through parallel sand formations. Whether or not this is economically feasible is a matter that has to be determined by the engineer for the particular field under consideration. What is presented here is the method for making the calculations for the composite recovery of wet gas from the sands.

The necessary conditions under which parallel flow can occur through several horizons are as follows: The sands have the same proved acreage and are identical as to boundaries and well locations. Each sand is uniform in thickness and permeability and either separated from one another by intermediate shale formations, or placed one over the other as bedding planes. The sands penetrated by each well have equal pressures and there is no vertical gradient to induce three-dimensional flow. If these conditions are met, say even approximately, then knowing the permeability, sand thickness, and porosity for each sand, the composite recovery for all the sands can be determined from the model analysis.

A typical recovery curve for the percent of wet gas originally present in a sand versus the percent of the total gas reserve processed is shown in Fig. 4. The curve is determined from Figs. 2 or 3 by planimetering the areas swept out by the dry gas in increased times. The straight portion of this curve corresponds to a production of 100 percent wet gas, with the increasing curvature indicative of the increased amounts of dry gas produced by the wells. The slope of this curve, however, is proportional to the instantaneous percent production of wet gas, and is shown plotted in Fig. 5.

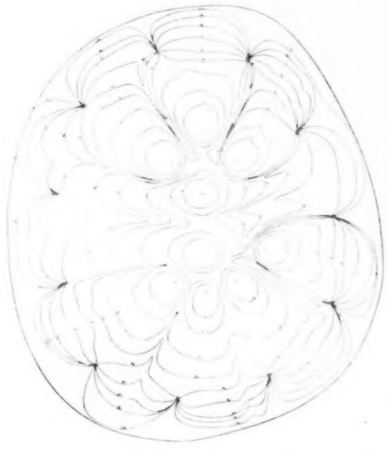


Fig. 3. Areas swept out by dry gas. Injection wells in center

It can be shown from the analytics of parallel flow[3] that the rate of gas cycled in each sand is proportional to the product of permeability and sand thickness. Further, that for any given instant in the operation, the percent of gas processed with respect to the total gas originally present in that horizon, is proportional to the permeability divided by the porosity of that sand.

Thus, for any time the relative amount of gas processed in each sand of a parallel system is related to the abscissa of Fig. 4 by this proportionality, and the corresponding points on the ordinate give the recoveries of the wet gas from the individual sands.

Example

As a sample calculation, employing this method, it will be assumed there are three sands arranged in parallel and conforming to the shape and orientation of the wells shown in Fig. 1. The first sand has a permeability of, say, 500 md., a porosity of 25 percent, and a sand thickness of 5 ft.; the second sand a permeability of 300 md., a porosity of 20 percent, and a sand thickness of 10 ft.; the third sand, a permeability of 100 md., a porosity of 18 percent, and a sand thickness of 20 ft. Then:

$$(K_1/\theta_1 : K_2/\theta_2 : K_3/\theta_3) = (500/25 : 300/20 : 100/18) = (20 : 15 : 5.56)$$

where θ is the porosity of the sand.

If we assume that the first sand has processed 100 percent of the gas originally in place in that formation, then the relative amounts of gas processed in the other two sands are expressed by the proportion as:

$100 \times 15/20 = 75$ percent for the second sand,

and

$100 \times 5.56/20 = 27.8$ percent for the third sand.

The corresponding recoveries of wet gas as read from the recovery curve, Fig. 4, are 67, 60, and 27.8 percent for sands one, two, and three, respectively. The total gas originally present in the sands is equal to the void space in the three sands and is proportional to:

$$(5)(0.25) + (10)(0.20) + (20)(0.18) = 6.85$$

The amount of wet gas recovered is equivalent to:

$$(67)(5)(0.25) + (60)(10)(0.20) + (27.8)(20)(0.18) = 303.6$$

The percent of wet gas recovered, therefore, with respect to the total gas originally in place is equal to:

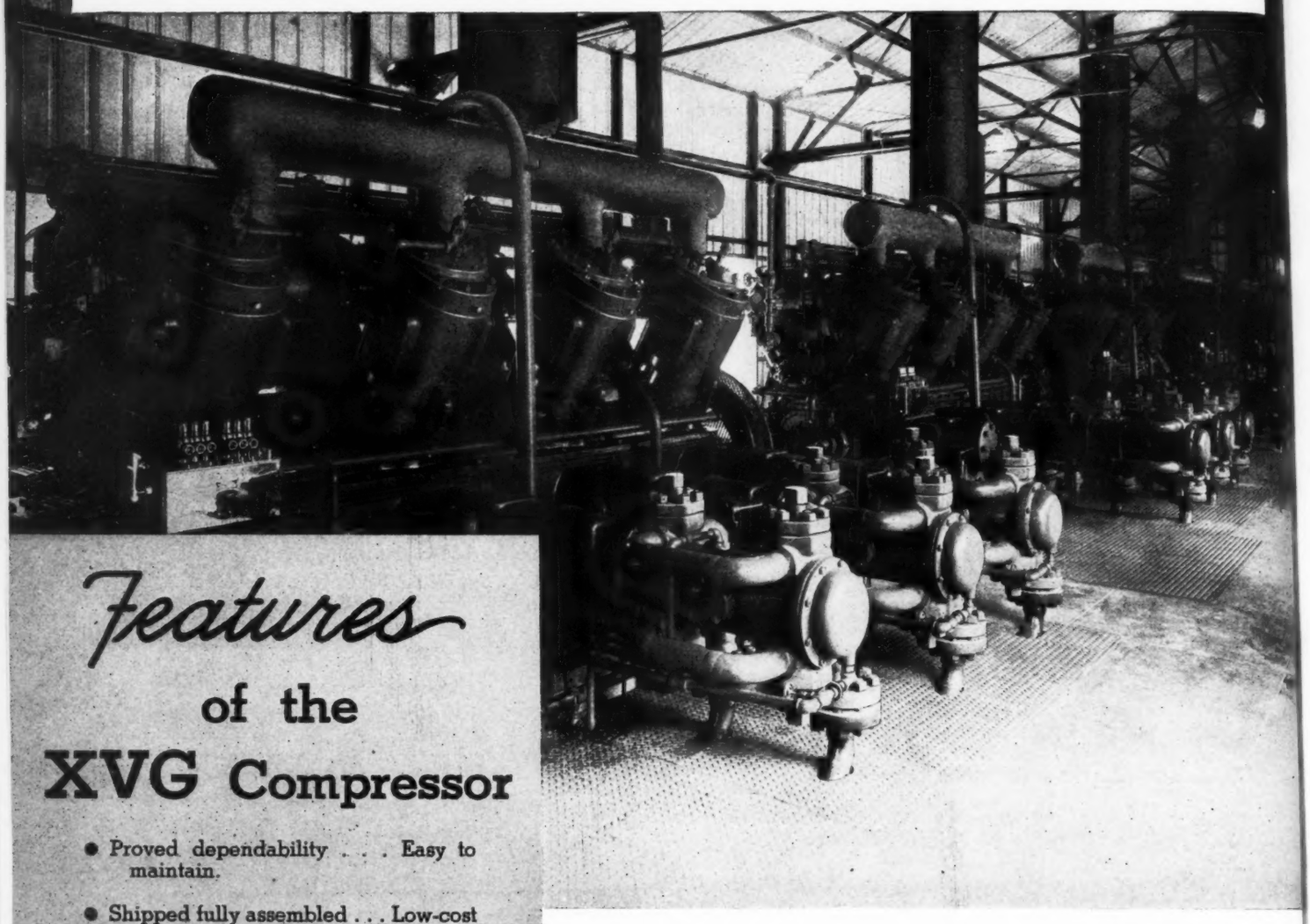
$$303.6/6.85 = 44.2 \text{ percent}$$

and the amount of gas processed from all three sands relative to the gas initially in place is given by:

$$\frac{(100)(5)(0.25) + (75)(10)(0.20) + (27.8)(20)(0.18)}{(5)(0.25) + (10)(0.20) + (20)(0.18)} = 54.7 \text{ percent}$$

This curve is shown plotted in Fig. 4. The corresponding instantaneous and cumulative curves for the compositions of the wet gas versus the total gas processed are given in Fig. 5. It is

The RECYCLING PLANT of H. M. Harrell



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significant to observe that for this combination of sands these characteristic curves do not offer as good a recovery as those for a single sand. This, however, should not be accepted as a criterion as the overall recovery of wet gases from these sands might be more desirable, but this in turn must be determined from the time factor and the economics involved.

Discussion

So far in this article the subject matter has been restricted to a discussion of the electrical model and its application to the study of gas cycling problems. Two methods have been reviewed: the electrolytic and potentiometric models, with a further discussion of the relative merits and limitations of each. Finally, the application of model analysis was presented as a means for fixing the extent of recovery of wet gas in processing several sands in parallel. This, then, brings us to a subject that the writer believes is most important, namely three-dimensional flow studies with electrical models.

The interpretation of three-dimensional studies with electrical models in the analysis of gas cycling problems has recently been given serious consideration. Heretofore, there has been a tendency within the industry to accept two-dimensional model studies as a panacea for all field studies, a practice that can not be expected to apply to every condensate field. Some thought, however, has been given to developing three-dimensional electrolytic models and mapping a colored wave-front as it appears to the eye or to a sensitized film. It must be added in this connection, however, that this procedure can only be considered as an approximation, as what appears to the eye is essentially two-dimensional flow and the third dimension is left unrecorded.

It is conceivable, however, that the electrolytic model can be employed for three-dimensional studies if the photograph of the wave travel could be brought out as a relief map. This would require stereoscopic photography similar to that used in aerial mapping. A rather novel method for doing this has recently been developed.[5] This method employs two cameras for taking pictures, and the resulting photographs are viewed with polarized light. Nevertheless, as to how successfully stereoscopic photography could be applied to electrolytic models is somewhat of a question, as in using agar gel models, say, the agar film must necessarily be thin and therefore would require extreme sensitivity in photography; further, the wave-fronts could be distorted due to the diffusional effects that have already been discussed.

[5] "Polaroid and Its Application to Aerial Photography and Photogrammetry," by John T. Rule, *Photogrammetric Engineering*, Vol. VII, pp. 31-39, Jan., 1941.

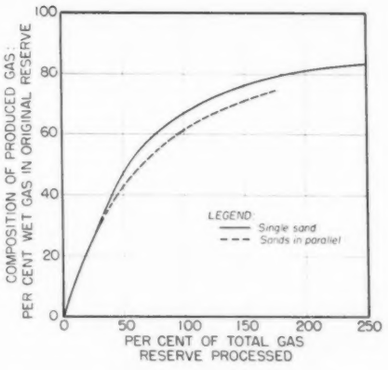
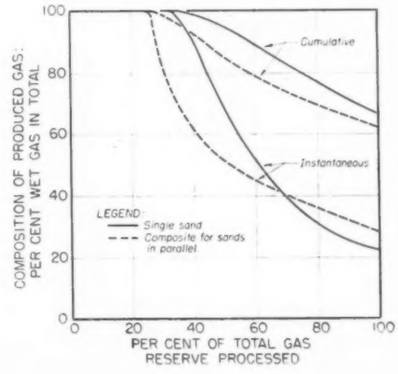


Fig. 4. Relationship between wet gas recovery and total volume of gas processed for a single sand and a combination of several sands in parallel

Another method for approximating three-dimensional flow has been suggested in the earlier paper[3] by using the potentiometric model. In this method the model is made to conform to the variations of the sand thickness as well as to the shape of the reservoir. The electrical mapping is made with the prober suspended entirely within the copper solution and touching the bottom of the model. The potential that is measured is a mean of the vertical distribution, and may not necessarily be a true null on the galvanometer but a minimum point. From these experimental data the potential contours, streamlines, and wave-fronts are drawn, similar to the two-dimensional problem. In determining the extent recovery of wet gas, however, the variation of sand thickness is taken into consideration in carrying out the graphical integration for the volumetric wave-front swept out.

Fig. 5. History of variation of composition of produced gas for a single sand and a combination of sands in parallel



As a check on this approximation the total current flowing and the voltage drop between maximum potential and minimum potential wells must be determined. Thus the current I equals:

$$I = \triangle V \triangle \psi / r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where r is the specific resistivity of the copper sulphate solution, $\triangle V$ the maximum voltage drop, and $\triangle \psi$ the overall flux difference, which can be determined algebraically from equation (5). This term, however, can also be calculated from the potential and streamline contours, corresponding to Fig. 1, and is equal to:

$$\triangle \psi = \int \left| \frac{d\Phi}{dS\psi} \right| H dS\Phi \quad . \quad . \quad . \quad (6)$$

where the integration sign indicates the integration completely around any given potential contour, with $\frac{d\Phi}{dS\psi}$ the rate of the potential drop per unit length of streamline, H the height of solution in the model, and $S\Phi$ the distance measured on the potential contour. Thus the values obtained for $\triangle \psi$ from equations (5) and (6) indicate the check on this approximation.

In cases, however, where the vertical permeability is known to vary, and assuming that a method for three-dimensional model study is available, it is possible to make the required adjustment to the dimensions of the model. Thus by a dimensional argument, which can be determined from the La-Place equation, it can be shown that the thickness squared of a given sand lens is in proportion to its permeability. When statistical data are available, therefore, it is possible to correct the increments of model height by this dimensional relationship to correspond to a sand of uniform permeability. After the wave-fronts are mapped for the model, however, they can be relocated in the actual sand and used to determine the extent of recovery of wet gas from the formation.

It is the writer's belief that the dry and wet gases are sharply defined in the formation without the diffusion of one gas into the other. This view is taken from the known fact that the diffusion of one gas into another is an extremely slow process, and the only way it is conceivable for the two gases in the formation to overlap is by a mixing process. Mixing can occur only by turbulent flow, however, and if D'Arcy's law applies the flow must be streamline. From the knowledge of gas movement in a sand formation, the travel is usually slow enough to satisfy the validity of D'Arcy's law.

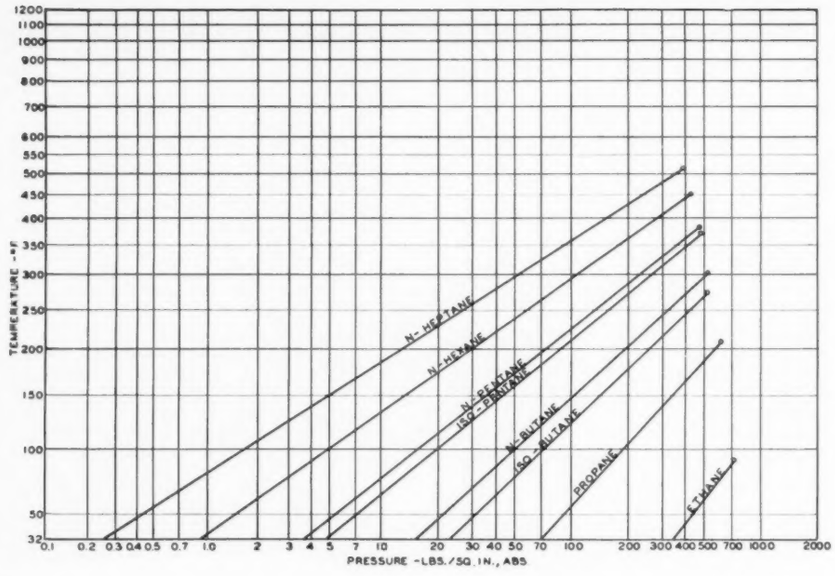


Fig. 1. Vapor pressure chart for hydrocarbons

Exclusive

by

F. D. Parker

Research Supervisor,
Union Oil Company
of California

Multicolumn Fractionation in the Natural Gasoline Industry

☆ Useful data on 1-, 2-, and 3-column operation emphasizes importance of stage fractionation in modern processing methods

PART 1

THIS article discusses the role that multicolumn fractionation plays in the preparation of essentially pure components, or narrow boiling cuts, from natural gasoline. By multicolumn fractionation is meant the separation by distillation of components or cuts in a series of fractionating towers so integrated in operation that one or all of the products from one tower comprises the feed or feeds to other towers in the series.

The reasons why multicolumn fractionation is significant at this time are basically three:

1. The market for liquid petroleum gases, both propane and butane, is expanding, and this requires the production of these products in maximum quantity and of satisfactory quality from natural gasoline stabilization.

2. The growth of the alkylation process has brought about a demand for *iso*butane, which is used in the process. Usually alkylation plants are situated at major refineries where considerable cracking is done inasmuch as olefins are required for the process, whereas natural gasoline is produced and stabilized to a considerable extent in the field. This demands that *iso*butane be produced in considerable quantity and of high quality to avoid shipping costs on relatively worthless inert fractions.

F. D. PARKER

received a bachelor of science degree in chemical engineering from the University of Michigan in 1935 and a master's degree from the same school in 1936—Did graduate work at the University of Michigan on distillation, 1936-38—Joined staff of Union Oil Company of California as process engineer, 1938—From 1940 to present has been research supervisor in charge of process development.

Another component that is gaining importance in the production of high octane aviation fuels is *iso*pentane, which also must be produced in considerable quantity and of high quality to be economically feasible.

3. This segregation of individual components of the lighter fractions of wild natural gasoline, principally propane and butane, is a requirement of certain processes now developed. In these the propane and butane are thermally or catalytically cracked and polymerized to gasoline or used to produce components that serve as the raw materials for the production of a large number of chemical products. Among the latter are such materials as synthetic resins and plastics, and synthetic rubber.

Introduction

Certain basic information must be outlined before a discussion of multicolumn fractionation can be conducted. It is not the purpose of this article to go into detail on the fundamentals of vapor-liquid equilibria, vaporization and condensation calculations, etc., as these subjects have been treated elsewhere.[1, 2, 3, 4] The points where these

[1]Brown, G. G., and Holcomb, D. E., *The Petroleum Engineer*, Jan.-Dec., 1940.
[2]Huntington, R. L., *The Refiner and Natural Gasoline Manufacturer*, Jan.-Dec., 1940.
[3]Robinson, C. S., and Gilliland, E. R., *Elements of Fractional Distillation*, McGraw-Hill Book Company, Inc., 1939.
[4]Bowman, *California Natural Gasoline Association*, May, 1939, meeting.

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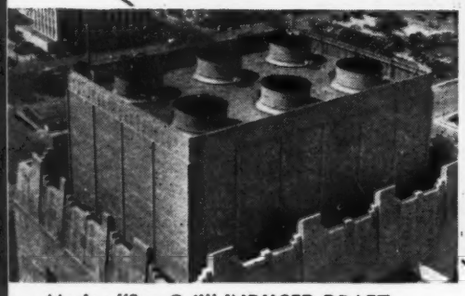

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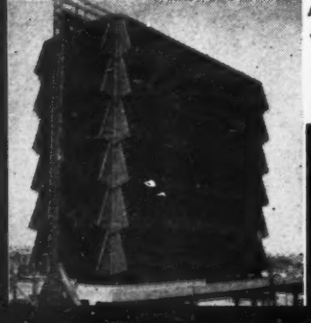

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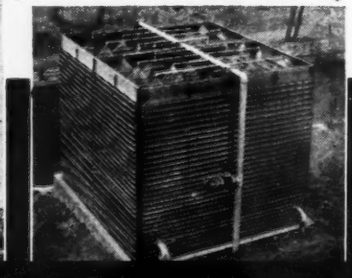

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phenomena bear upon the problem at hand will, however, be reviewed briefly.

First, it is necessary to recognize the composition and nature of the material that we are attempting to fractionate. The lighter fractions of wild natural gasoline (condensate from compression plants or stripping still overhead from absorption plants), listed in order of decreasing volatility are as follows: methane, ethane, propane, *iso*butane, normal butane, *iso*pentane, normal pentane, and residue (hexanes and heavier). The first five of these components (methane through normal butane) are gaseous at normal conditions of temperature and pressure. The butanes, both *iso*- and normal and to a lesser extent propane, may occur under normal conditions of temperature and pressure as liquids when dissolved in heavier constituents, such as the pentanes and the residue consisting of hexanes and heavier.

An appreciation of the volatility of the components is in order before discussing the separation of one from the other by distillation. Fig. 1 is a vapor pressure chart for pure hydrocarbons on which is plotted the vapor pressure of the compounds, ethane through normal pentane, as a function of temperature. The coördinates for this chart are purely arbitrary ones with regard to spacing such that the vapor pressure of individual hydrocarbons when plotted thereon appears as a straight line. This chart is similar to that issued by the California Natural Gasoline Association last year.

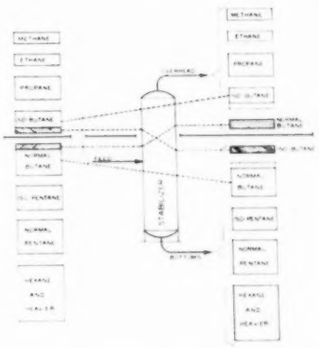


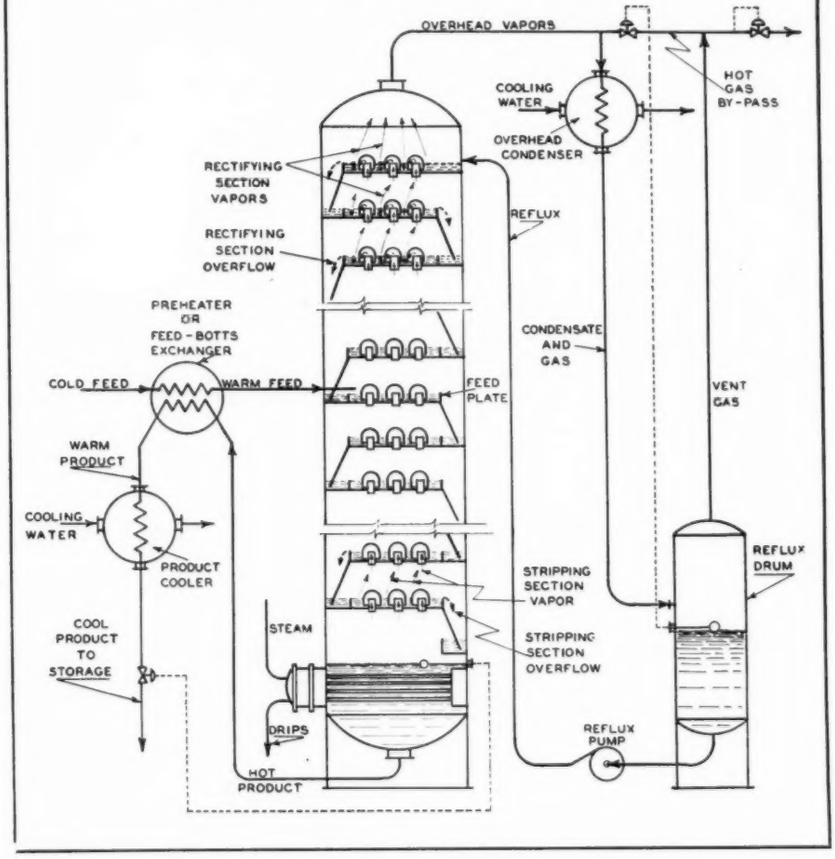
Fig. 2. Diagram showing operation between key components and natural gasoline stabilization

Table 1 lists significant properties of the components propane, *iso*butane, normal butane, *iso*pentane, and normal pentane.

In dealing with mixtures of hydrocarbons we frequently encounter one or more of the components at conditions of temperature and pressure widely different from those that would be characteristic of the vapor pressure of the pure component itself. For example, propane exerts a vapor pressure of 190 lb. per sq. in. absolute at a temperature of 100°F. but it can exist as a liquid in solution in gasoline at a temperature of 100°F. and a pressure of only 15 lb. per sq. in. absolute. Also *iso*pentane, which exerts a vapor pressure of 19.7 lb. per sq. in. absolute at 100°F., can exist as a vapor at a temperature of 100°F. and a pressure of 400 lb. per sq. in. absolute in the presence of some lighter materials, such as methane and ethane. The effective vapor pressures of hydrocarbons at conditions of temperature and/or pressure appreciably different from those corresponding to the pure materials are considerably different from the pure component vapor pressures as drawn in Fig. 1. This vapor pressure deviation phenomenon was ably discussed in a paper by Bowman.[4] The actual vapor pressure and resultant vapor-liquid equilibrium is expressed for convenience in terms of $K = y/x$ in which y equals the mol fraction of the component in question in the vapor phase and x equals the mol fraction of that same component in the equilibrium liquid phase. This ratio, y/x, is a function of the total composition of the system, including both liquid and vapor phases, in addition to the temperature and pressure of the system. Actually, it has been found that for components of natural gasoline over a wide range of conditions, this ratio y/x can be expressed in terms of the convenient variables of temperature and pressure, so that a plot of y/x, or K, against temperature for a given component has a shape roughly similar to that of the vapor pressure relationships of Fig. 1. The principal difference is that a component existing in a system under a total pressure greater than its true vapor pressure exerts an effective vapor pressure higher than its true vapor pressure; and a component existing in a system under a total pressure lower than its normal vapor pressure exerts an effective vapor pressure lower than its true vapor pressure.

Table 2 lists the $K = y/x$ values for the components ethane, propane, *iso*butane, normal butane, and *iso*pentane. These values are given at temperatures of 100°F., 150°F., 200°F., and 300° F., and at pressures corresponding to

Fig. 3. Diagram showing operation inside distillation column



those that would be encountered in fractionators effecting separations between a pair of components. Thus, the $K = y/x$ values for the components ethane and propane are given at 600 lb. per sq. in. abs. (585 lb. per sq. in. gauge), which is the approximate pressure required to effect condensation of ethane overhead at a temperature of 85°F. obtainable with ordinary atmospherically cooled water. Similarly, the $K = y/x$ values for the pair *iso*pentane and normal pentane are given at a pressure of 30 lb. per sq. in. abs. (15 lb. per sq. in. gauge).

The four right-hand columns of Table 2 present the ratio of K's for each pair of components. This ratio value is called the "relative volatility" and is obtained by dividing the "K" for the lighter component of each pair (for example, ethane, in the ethane-propane pair) by the "K" for the heavier component at the same temperature and pressure. At 600 lb. per sq. in. abs. and 150°F., ethane has a $K = y/x$ of 1.6 and propane a $K = y/x$ of 0.65 so that the ratio of K's (relative volatility) is $1.6/0.65 = 2.5$. Also, at 90 lb. per sq. in. abs and 150°F., *iso*butane has a $K = y/x$ of 1.5 and normal butane a $K = y/x$ of 1.2; consequently the ratio of K's (relative volatility is $1.5/1.2 = 1.3$.

The vapor above a liquid mixture containing equal amounts of ethane and propane at 600-lb. pressure and 150°F. (conditions such as might occur on a plate in a high-pressure stabilizer), will be composed of ethane in a concentration 1.6 times its concentration in the liquid, and propane in a concentration only 0.65 its concentration in the liquid. It follows that the ethane and propane concentrations in the vapor will be in the ratio of $1.6/0.65 = 2.5$ and the vapor will be considerably richer in the lighter component ethane, and considerably leaner in the heavier component propane than the liquid with which the vapor is in equilibrium. This is the mechanism by which distillation effects separation of materials of different volatility.

A feed containing components in various concentrations is introduced into a distillation tower and the vapors become richer in the lighter components than they do in the heavier components because of differences in volatility. The action of a fractionating tower is to effect a succession of vaporizations and condensations on the trays and in so doing the vapors rising to the top of the column become progressively enriched with respect to the lighter components and the liquid flowing to the bottom of the tower becomes progressively enriched with respect to the heavier components.

General Notes on Fractionation

Fig. 2 is a schematic representation of the type of fractionation by distillation commonly encountered in the natural gasoline industry. Feed, consisting of the components methane, ethane, propane, *iso*butane, normal butane, *iso*pentane, normal pentane, and a residual fraction described as hexane and heavier, is pumped to a stabilizer tower that may operate at a range of pressures from 150 to 300 lb. per sq. in. abs. The relative magnitude of the components present is indicated by the size of the blocks representing each individual component, and the composition thus indicated is comparable to that characteristic of wild natural gasoline produced by low-pressure absorption. The pictorial representation shows a separation between *iso*butane and normal butane being accomplished in the stabilizer. For the feed stock considered this corresponds to the production of 22-lb. Reid vapor pressure gasoline. A substantially complete recovery of all normal butane present in the feed is required. Because normal butane has a lower vapor pressure than *iso*butane, it is desirable to include in the gasoline virtually all the normal butane in the feed with a minimum inclusion of *iso*butane and a minimum loss of normal butane overhead. A greater overall volume of 22-lb. Reid vapor pressure material is produced thereby. The problem of stabilization in this case becomes a problem of separating the *iso*butane and the normal butane components in the feed, and these components are called the "key" components. The separation between *iso*butane and normal butane is not perfect, and a quantity of *iso*butane appears in the 22-lb. Reid vapor pressure gasoline and a quantity of normal butane appears in the overhead. This is shown schematically in Fig. 3, wherein the shaded areas represent *iso*butane and normal butane, which appear where they are not desired, namely, in the stable gasoline and in the overhead. The separation between the propanes and *iso*pentanes need hardly be considered, for these components have a relative volatility far greater than that of *iso*butane and normal butane, such that a reasonably effective separation of *iso*butane from normal butane will result in a substantially complete separation of propane from *iso*pentane.

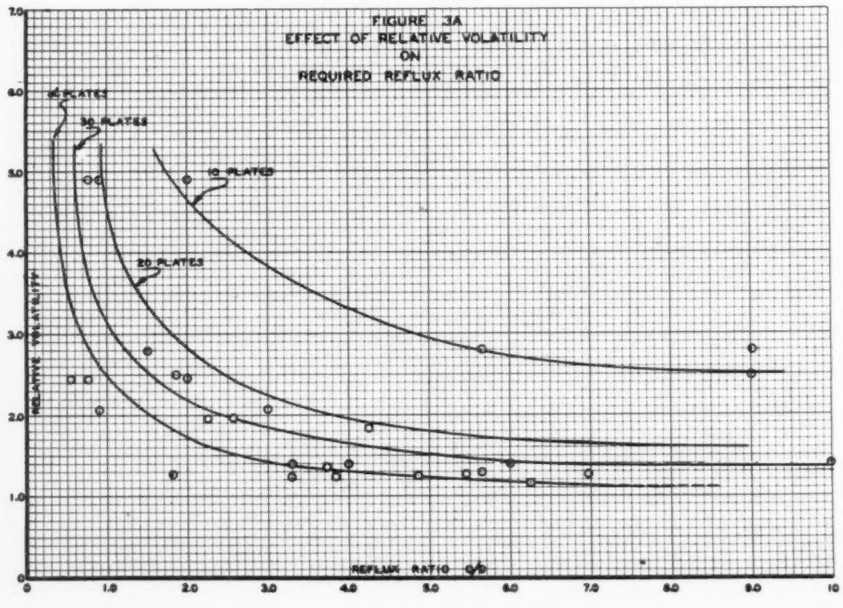
The concept of the key components is a very useful one when considering the actual gasoline stabilization or fractionation.

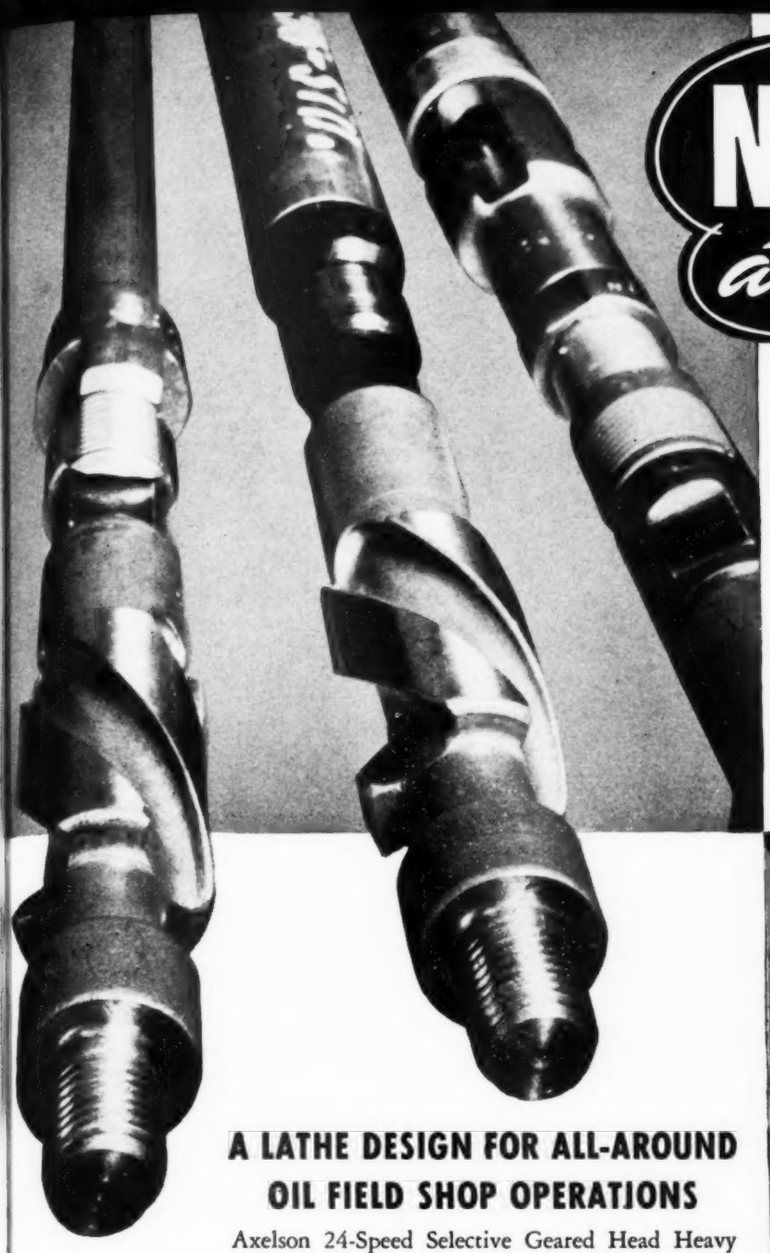
Fig. 3 is a somewhat more detailed drawing of the column effecting this separation, and shows the processes going on inside the column whereby the separation is effected. Although only a single column is shown, the internal processes are common to each unit of

TABLE I
Properties of the lighter components of natural gasoline

Component	Vapor pressure at 100°F. lb./sq. in abs.	Knock rating A.S.T.M. motor
Propane	187	..
Isobutane	72	99
Normal butane	50.5	90
Isopentane	19.7	90-93
Normal pentane	15.7	66

Fig 3A. Effect of relative volatility on required reflux ratio





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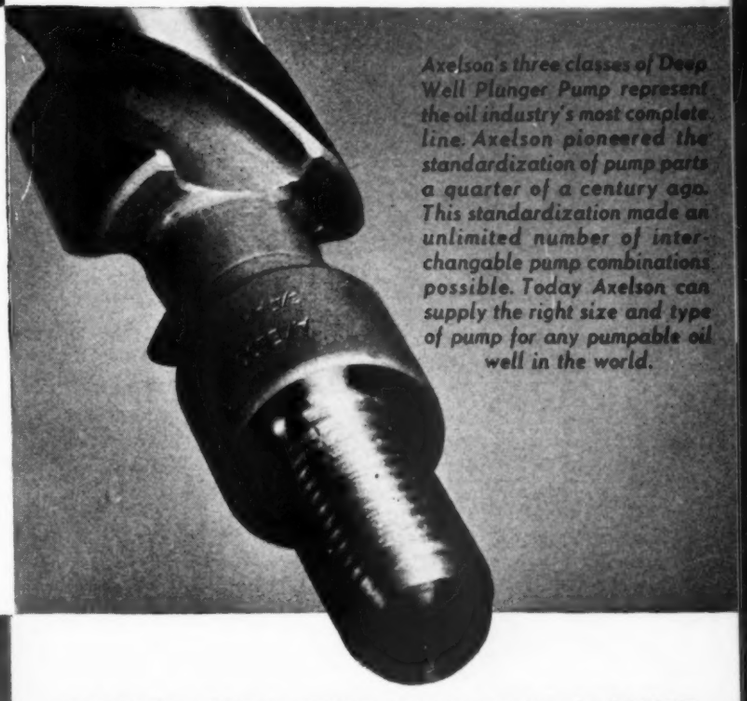

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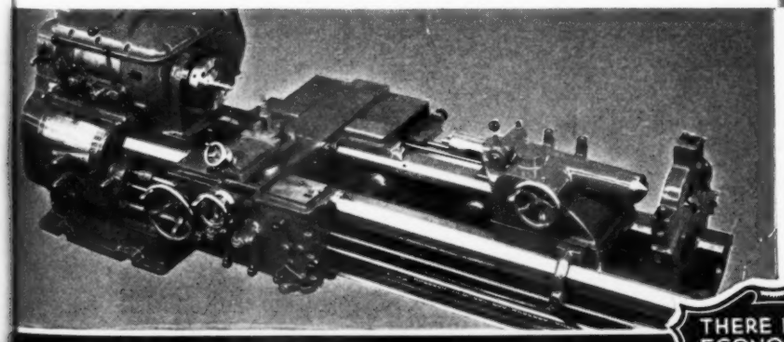

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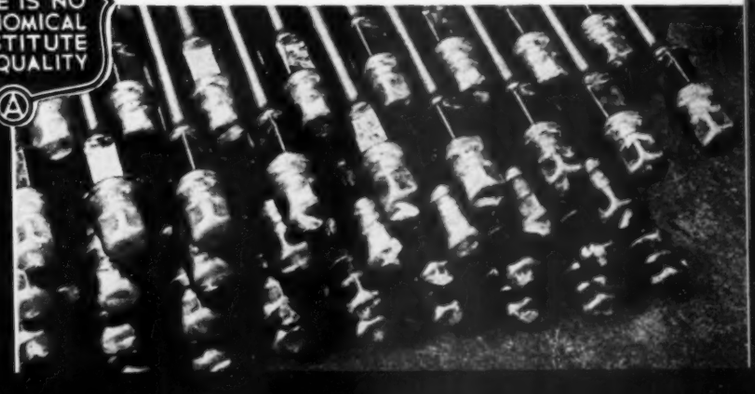

a multicolumn fractionator installation.

Cold feed, consisting of raw natural gasoline from the accumulator, is pumped through an interchanger extracting heat from the hot stable gasoline product. The warm feed then enters the stabilization column. A reboiler situated in the bottom of the column consists of a shell-and-tube type exchanger using steam for the heating medium. Steam is condensed, thereby liberating its latent heat, which in turn vaporizes a portion of the gasoline bottoms surrounding the tube. These vapors rise through the lower trays of the column, contacting a down-flowing liquid stream as discussed below. The overhead consisting of the net butanes and lighter produced by stabilization and the cycling reflux stream flows through a condenser coil. At an operating pressure of, say, 250 lb., the overhead is totally condensed and accumulates in the reflux drum. The reflux pump returns the reflux cycle to the top of the tower. As more feed is run to the column and the quantity of overhead increases correspondingly, a float in the reflux drum actuates a bypass in the overhead vapor line around the condenser so that hot gases comprising the net overhead from the column are produced. Cool reflux returned to the top plate is vaporized through contact with hot vapors rising through the upper plates of the column and is cycled through the condenser to the reflux drum and back to the top of the column, extracting a certain amount of heat during each cycle. This heat is removed from the hot vapors rising through the top plates of the column, effecting a condensation of a portion of these vapors. Warm condensate from the top plates of the column flows downward and contacts the hotter vapors in the lower trays, and effects their condensation and the revaporization of the condensate from the upper trays. There is set up within the column, therefore, a series of vaporization and condensation cycles whereby vapors from the lower trays of the column condense on trays higher in the column and return to the lower trays to be again vaporized by hotter vapors rising from below. This repeated vaporization and condensing enriches the vapors with respect to the more volatile components and enriches the liquid with respect to the less volatile components in the manner described earlier in this article.

The gasoline consisting of the residue of hexanes and heavier, normal pentanes, the *iso*pentanes, the majority of the normal butanes from the feed, and a portion of the *iso*butanes from the feed is then produced as bottoms from the tower. The hot gasoline bottoms are cooled first by interchange with the cold feed to the column and then by cooling water and then are produced to storage.

The vapor stream at any point in the upper part of the column, which consists of (1) the cycling vapor (that which condenses on a higher tray and is returned for revaporization below) and (2) the overhead vapor production, is called the rectifying section vapor. The liquid at the corresponding point, which consists of (1) the cycling liquid (that which is vaporized on the lower trays) and (2) that which finally appears in the bottoms product, is called the rectifying section overflow. The ratio of rectifying section overflow to rectifying section vapor expressed in comparable units such as pounds of rectifying section overflow to pounds of rectifying section vapor or mols of rectifying section overflow to mols of rectifying section vapor, determines in large measure the degree of fractionation that will take place in the rectifying section.

The corresponding quantities in the lower part of the tower are called the stripping section vapor and stripping section overflow. The ratio of stripping section overflow to stripping section vapor in a manner similar to the effect noted in the rectifying section, determines in large measure the degree of fractionation obtained in the stripping section.

Another major item determining the degree of fractionation in both the rectifying and stripping sections of the tower is the number of plates in each section, which obviously determines the number of vaporizations and condensations that will take place therein. The greater the number of plates for a given ratio of overflow to vapor, the sharper the separation. Generally the closer the ratio of overflow to vapor for a given number of plates, the sharper the separation. It is clear that the ratio of overflow to vapor in the rectifying section must always be less than 1, or by material balance the vapor equals the reflux plus the overhead vapor. The ratio of overflow to vapor in the stripping section must always be greater than 1, or by material balance the overflow must equal the vapor plus the bottoms product.

Fig. 3A is a rough plot to illustrate the significance of relative volatility on reflux ratio for fractionation. This chart plots relative volatility for the key components to be separated vs. required reflux ratio expressed as volumes of reflux per volume of overhead product. Lines for various plate numbers are sketched in approximate location. It will be noted that the required reflux ratio increases as the relative volatility approaches 1.0 and reaches infinity at this value. That is, no amount of reflux or plates can effect the separation of components of identical K values by simple distillation. The smaller the relative volatility, the more difficult the separation; hence referring to Table 2, the separations encountered in natural gasoline work, listed in order of increasing difficulty are:

Ethane from propane
Normal butane from *iso*pentane
Propane from *iso*butane
*Iso*butane from normal butane
*Iso*pentane from normal pentane

and the respective reflux ratios required are approximately:

1.5 to 1.0
2.5 to 1.0
3.0 to 1.0
6.0-8.0 to 1.0
10.0-12.0 to 1.0

(EDITOR'S NOTE: To be continued in an early issue.)

TABLE 2

Variation of equilibrium constants with temperature and pressure

Separation	Pressure for condensing at 85°F. lb./sq. in. abs.	K=y/x at pressure and				Relative volability at pressure and			
		100°F.	150°F.	200°F.	300°F.	100°F.	150°F.	200°F.	300°F.
Ethane from propane	600	1.2 0.37	1.6 0.65	1.9 0.92	2.7 1.6	3.3	2.5	2.1	1.7
Propane from Isobutane	175	1.1 0.51	1.7 0.86	2.4 1.3	4.6 2.7	2.2	2.0	1.8	1.7
Propane from Isobutane	250	0.78 0.39	1.25 0.66	1.8 1.0	3.4 2.0	2.0	1.9	1.8	1.7
Isobutane from normal butane	90	0.85 0.63	1.5 1.2	2.4 1.9	4.9 4.0	1.3	1.3	1.3—	1.2+
Normal butane from Isopentane	75	0.75 0.29	1.4 0.6	2.2 1.1	4.7 2.7	2.6	2.3	2.0	1.7
Isopentane from normal pentane	30	0.66 0.53	1.4 1.25	2.6 2.3	6.5 5.8	1.2+	1.1+	1.1+	1.1+

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By Ralph C. Graham

District Engineer, Security Engineering Company, Inc.

SUCKER rod pumping, using the cold-drawn common working barrel and traveling valve equipped with valve cups, is one of the oldest forms of fluid lift in the oil industry. Moreover, the greater proportion of pumping wells in stripper areas today still use this as the most economical method. Manufacturers of pumping equipment have greatly improved the component parts of this system, including the valve cups. Many operators, however, are not reaping the benefits to be gained by the improved valve cup, and in a great number of cases the fault is entirely their own.

Several reasons for this are apparent. First, the installation of valve cups is an old procedure and has been handed down from rod crew to rod crew with little variation. Second, the low cost of the cups themselves has created the opinion that any investigation of their use would be uneconomical as cups are an item of too small a cost to justify the time and effort required for a thorough study. Too often the fact that it requires money for pulling crews and equipment to make these changes is overlooked. Also the lost oil production while a well stands idle will amount to a sizable quantity if cup jobs are frequent. With rising crude oil prices now prevalent, operators might well increase their profits by investigating the frequency of their pulling jobs.

Although the valve cup is the smallest item of expense in the pumping equipment, the success or failure of the entire assembly is dependent upon its performance. With this thought in mind, an exhaustive study was made of more than 600 wells for a three-year period to determine whether downtime could not be reduced by proper selection of valve cups. Pools having typical reservoir conditions were chosen so that proper grades of hardness as well as correct cup size could be determined. From the group of pools two were selected for specific tests as it was believed that conditions in these fields more nearly represented typical stripper areas.

In beginning this study, it was realized that the human element was of vital importance and that so far as possible this variable should be controlled in order that each installation would have similar treatment. The first factor to consider, therefore, was the education of the pulling crews since their failure to function correctly would nullify all the other efforts expended to eliminate mechanical differences.

Care of Cups Prior to Service

Valve cups are usually carried in their original boxes by the pulling crews until they are needed and then placed upon the traveling valve. This is done to prevent damage to loose cups and to prevent cups of various sizes and hardness from becoming mixed. By this method the cups are assembled on the valve in a dry condition and first contact the oil as the valve is lowered into the hole.

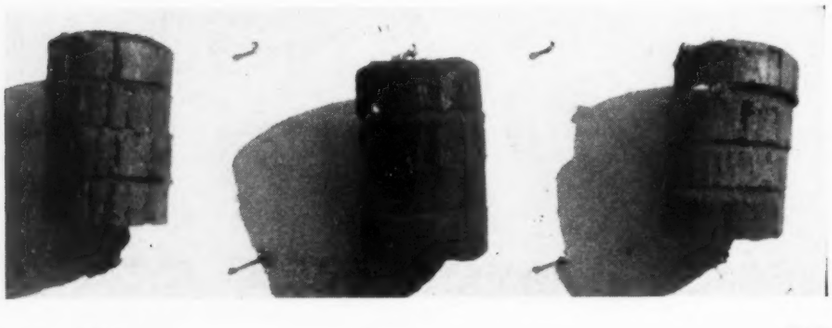
To obtain maximum performance, cups should be permitted to soak in the fluid in order to absorb the oil before the pumping operations begin.

If a well is pumped the moment the replacement is completed, it is probable that the life of the cups will be materially shortened. The resultant action can well be likened to the starting of a gas engine. It is well known that the greatest wear on piston rings occurs when the engine is first started due to lack of instantaneous lubrication. Inasmuch as valve cups are in reality the piston rings of the pump, a similar severe initial wear occurs if they are pumped before they have had

RALPH C. GRAHAM

graduated from Missouri School of Mines in 1931, receiving his degree in petroleum engineering—Was employed by various major oil companies in the Mid-Continent area until 1939 when he entered the employ of The Security Engineering Company, Inc.—After a year in the main office of the company at Whittier, California, was transferred to the position of district engineer in the Houston, Texas, office.

Fig. 1. Three sets of cups showing the damaging effect of scored working barrels



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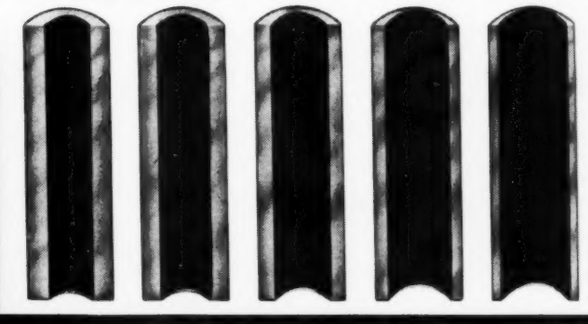

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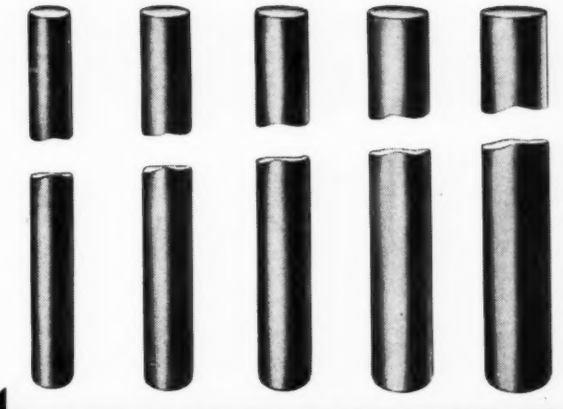

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Fig. 2 Fig. 3 Fig. 4 Fig. 5

Illustrating special cup designs on which comparative data were gathered during test

time to absorb oil. When wells are pumped full time and the loss of oil resulting from allowing the well to remain idle after cup replacement would be uneconomical, the better policy would be to soak the cups in oil before they are installed. In order to avoid confusion, they should then be repacked in the original boxes for transportation to the well. This allows the cup to absorb the oil and become more flexible, thereby obtaining a good seal on the first stroke rather than working dry for some time before absorbing oil and adapting itself to the barrel. When cups cut out rapidly, many times the cause can be traced to the fact that the dry cups were pumped immediately and they did not have a chance to absorb oil and become flexible. This permitted bypassing that resulted in the cup being cut-out before it had an opportunity to form a good seal. If possible, therefore, when the cups must be run dry, it is better to permit the well to set a sufficient length of time so that the cups can absorb oil and adjust themselves to the working barrel.

Methods of Cup Installation on Valve Bodies

In analyzing data to determine the expected life of a certain type cup, erroneous conclusions are apt to be drawn if all cups tested do not undergo the same conditions. Although it is recognized that it is impossible to maintain the same reservoir conditions in an oil well over a long period of time, it is possible to have the mechanical equipment in first-class condition for each test. It would, of course, be impractical to install a new traveling valve with each cup replacement, but it is possible for the rod crew to carry a small mill file and smooth off the burrs and rough edges that invariably occur on the cup followers. If these are not removed, they tend to cut the shoulder of the new cup when the valve is made up. Further tightening produces a cutting action from these rough edges along the cup shoulder with a resultant breakdown in the resistance of the cup. The cup is unavoidably subjected to a great amount of flexing movement during operation, and when the fiber strength is reduced by cutting, the cup is comparatevely short-lived. Badly battered followers should be replaced rather than an attempt to get additional service from them.

In making-up the followers, care must be taken to see that the assembly is not made-up too tight. The followers are supposed to hold the cups firmly in place, but often they are made-up too tight in the erroneous belief that this is beneficial. Followers made-up too tight tend to break the cup shoulder and an action similar to the cutting effect is obtained. This excessive tightening is done in nearly every case in the belief that such a procedure will spread the cups and make a better seal. This has been proved false by carefully gauging cups that have been tightened by various amounts, and in no case could perceptible increase in gauge be detected. To overcome this tendency a larger size cup should be advocated if the records show that the previous cups were too small.

Importance of Working Barrel Condition

Close observation of removed cups reveals much. It is possible to detect a scored barrel in its earliest stages by examining the cups. Fig. 1 illustrates three sets of cups that indicate scored barrels. The deep, continuous gash along the sides of all four cups in each of the three sets indicates that fluid was bypassing the cups and that in all probability a similar cutting action was occurring on the bore of the pump. Each of these sets of cups was pulled after a short period of useful life for inspection and then the barrel was pulled for observation. A rigid inspection of the barrel showed a small lon-

TABLE 1

Force Required to Install New Cups in New Working Barrels

Size of cup[1]	Size of barrel, in.	Force in lb. required to enter cup into barrel				Force in lb. required to begin movement of valve in barrel				Force in lb. required to continue movement of valve	
		1st cup	2nd cup	3rd cup	4th cup	1st cup	2nd cup	3rd cup	4th cup	minimum	maximum
1½" (—0.015)	1.5012	12[2]	16	20	20	8	6	8	12	4	8
1½"	1.5012	12	16	20	30	16	20	24	24	6	10
1½" (+0.015)	1.5012	24	36	48	48	40	50	60	60	16	20
1½" (+0.030)	1.5012	60	90	100	100	70	80	90	90	32	40
1½" (+0.045)	1.5012	50	60	130	170	160	176	176	176	90	90
1¾"	—[3]	no scale registration.									
1 25/32" (—0.015)	—[3]	8	12	16	16	8	12	12	12	4	4
1 25/32"	—[3]	24	32	44	50	40	44	44	44	12	16
1 25/32" (+0.015)	—[3]	50	60	80	80	72	80	80	80	20	28
1 25/32" (+0.030)	—[3]	100	140	160	160	120	130	140	140	40	50
1 25/32" (+0.045)	—[3]	300	372	500	660	500	600	600	600	200	250

[1]All cups measured carefully to determine whether cups conform to exact size as marked.
[2]Forces indicated are same for hard, medium, and soft cups.
[3]Measurement of barrel varied—1.7808 in upper portion, 1.7818 in lower portion. A.P.I. standard is 1.7810.

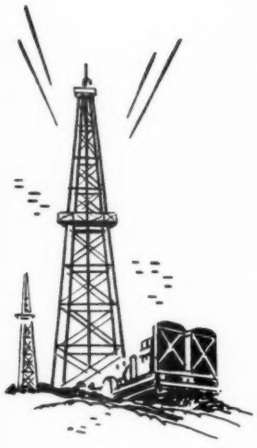
TABLE 2

POOL A

Comparative Service Record of Valve Cups Having Different Degrees of Hardness

Well no.	Well depth, ft.	Daily production, bbl.		Pumping time, hr.	First run		Second run		Third run		Fourth run		Average life	
		Oil	Water		Type	Hours service	Type	Hours service	Type	Hours service	Type	Hours service	Hard cups	Medium cups
1	1092	9	1	24	1 25/32H	700	1 25/32+15H	904	1 25/32+15H	1488	1 25/32+15M	11544	1030	11544
2	1203	14	2	9	1 25/32+15H	873	1 25/32+30M	4248	1 25/32+15M	2826			873	2543
3	1202	1	1	2	1 25/32+15M	114	1 25/32+15H	88	1 25/32+15M	298	1 25/32+15M	336	88	247
4	1145	2	2	16	1 25/32+15H	720	1 25/32+15M	976	1 25/32M	888	1 25/32+15M	756	720	866
5	1109	7	5	9	1 25/32+15H	216	1 25/32H	288	1 25/32+15M	1260	1 25/32+15M	1845	252	1553

NOTE: H indicates hard; M indicates medium.
+15, +30 denote plus 0.015 in. and plus 0.030 in., respectively.



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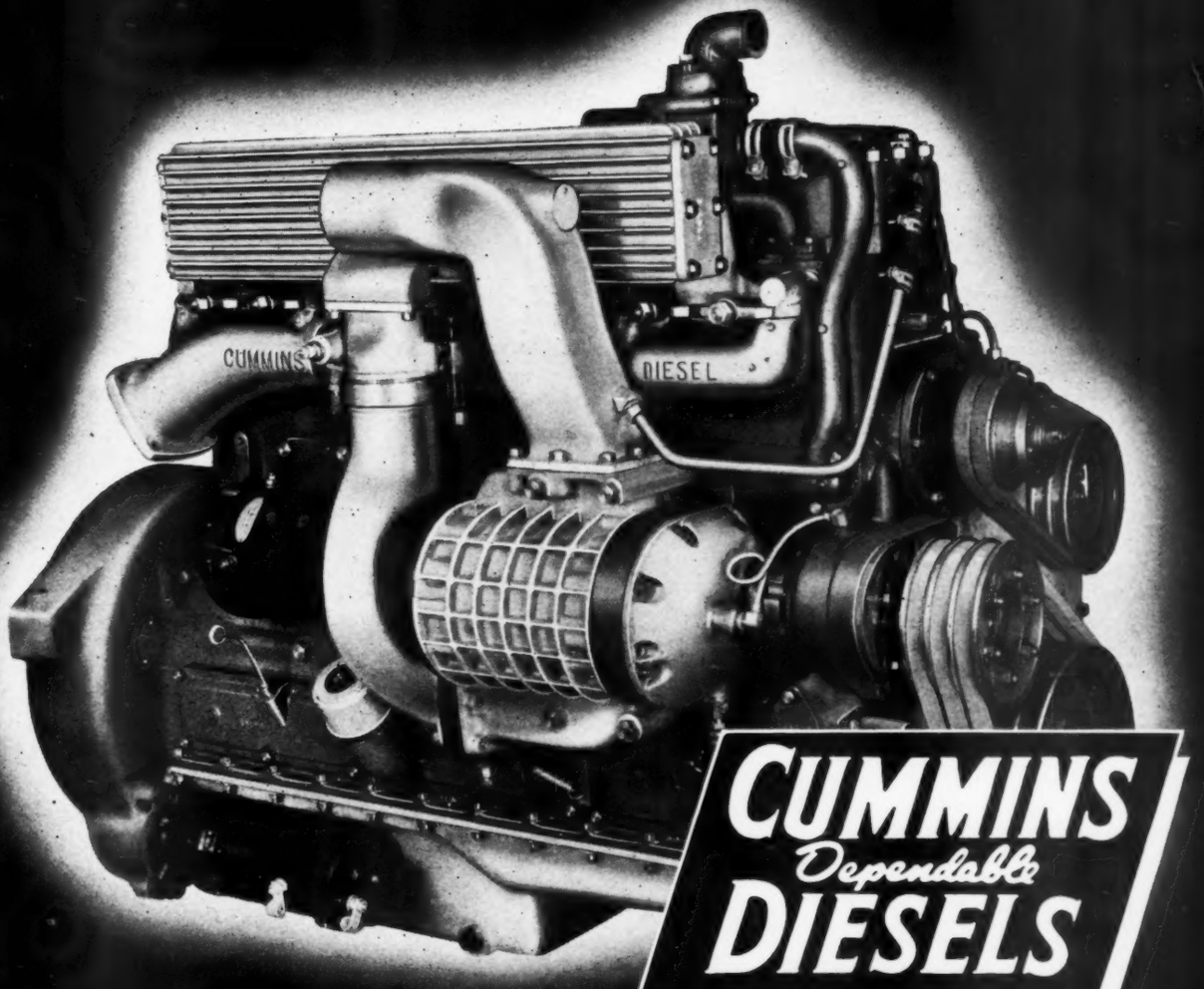

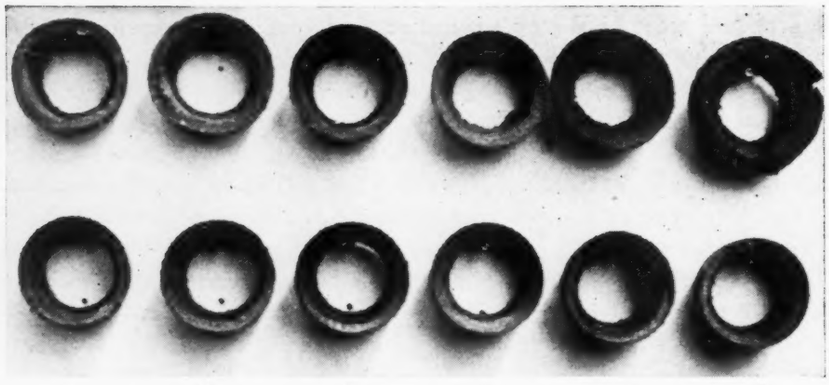

A B C D E F

Fig. 6. Cups were boiled for 10 hr. in oil as severe test of durability

gitudinal groove, almost imperceptible, coinciding in length with the length of the pump stroke. Any succeeding cup replacement would have been of little value inasmuch as the fluid would immediately begin to bypass the new cups through this small groove. It would be only a short period of time until they would be cut-out similar to the cups illustrated in Fig. 1. Deeply grooved cups such as illustrated usually indicate a scored working barrel and should be a ready guide in determining working barrel replacements. When a scored barrel is discovered, in no case should repeated runs be made in an attempt to remedy the trouble as tests show that it is of little use to try to fit a valve cup to any surface except a smooth bore.

Determining Correct Cup Size

Correct cup size, too, has been more or less overlooked. Table 1 gives an average of several tests run to determine the actual pull in pounds necessary to enter, move, and work a dry cup in a common working barrel. Contrary to common opinion, very little additional force is needed for the oversize cups. A.P.I. standards allow a tolerance of plus or minus 0.0082 in. in working barrel inside dimensions and a tolerance of plus or minus 0.005 in. in outside diameter of cups. If these two tolerances were to act in opposite directions, it would require an oversize cup to pump as efficiently as a regular cup if no tolerance were encountered.

Gauging working barrels before running would rectify this discrepancy, but as a rule this results in little benefit as inside diameters are not always consistent throughout the length of the barrel, and taking inside measurements requires both skill and the necessary inside micrometers to obtain readings as accurate as would be essential. It is recommended that properly dressed valves with a graduation of sizes be stocked ready to run in a new barrel for a test, and in this manner it would be possible to determine which size cup would be most suitable. Table 1 shows that with a $1\frac{25}{32}$-in. barrel very little extra force is needed to move the plus 15-thousandths cups, and the additional packing-off effect would increase the pump efficiency. With this thought in mind, it is advocated that plus 15-thousandths cups be run in new barrels and plus 30-thousandths cups in used barrels. Caution must be taken, however, not to fit a cup too tightly as this would increase the frictional drag and possibly accelerate sucker rod breakage. The cups should fit just tightly enough to prevent fluid slippage.

Effects of Special Cup Design

During the period of testing, cups of special design were run to gain comparative data on length of service. Fig. 3 illustrates a cup design incorporating a steeper bevel than is used on the standard cup shown in Fig. 2. The initial runs of these cups indicated a life of only 25 percent as long as the standard design. Additional runs in other areas substantiated the results. The conclusion was drawn that the variance of the bevel in small increments had little to do with the performance of the cup, with the exception that too steep a bevel would materially lessen the service. The sealing effect of a cup is accomplished by the pressure exerted equally against the sides by the hydrostatic head. This pressure is exerted on the upstroke and the cup has a tendency to bulge, whereas on the downstroke the pressure is relieved and the side walls of the cup resume their normal shape. Fig. 4 illustrates the shape of a cup removed after ideal performance. This shows that wear occurs just above the shoulder rather than at the lip of the cup. A good cup then should be both strong and flexible at the shoulder inasmuch as all the load is absorbed at that point.

Fig. 5 illustrates an inverted bevel type cup similar to a seating cup. This construction is based upon the principle of a fluid pack, such as employed on metal plunger pumps, combined with the sealing effect of the cups. Although the principle seemed sound, the tests failed to give the desired results. Selecting a well on which prior records were available to base comparison, these cups were installed and had a total length of service of 336 working hours as compared to a previous run of 1568 hours and a succeeding run of 728 hours with standard cups of the same size and hardness. As a consequence no other runs of this type cup were made, and their use was discontinued.

Cup manufacturers now make valve cups according to A.P.I. standards; that is, having three degrees of hardness and a graduation of sizes by thousandths. Tolerances in sizes are set by A.P.I. standards, but it was found in carefully gauging cups for the tests that some manufacturers did not adhere to the standards as closely as others and that some discrepancy occurred as a result of this variance. Although cup manufacture is more or less the same, the ingredients used vary with the different special processes, such as heat treatment and degree of bevel. Cups are plies of composition material held together with a vulcanizing agent that is heated and cured to

TABLE 3

POOL A

Comparative Service Record of Oversize Valve Cups Used to Compensate for Wear

Well no.	Well depth, ft.	Daily production, bbl.		Pumping time, hr.	First run		Second run		Length of service	
		Oil	Water		Type	Hours service	Type	Hours service	normal installation	oversize installation
1A	1106	9	0	24	$1^{25}/_{64}$M	768	$1^{25}/_{64}$+30M	4248	768	4248
2A	1185	8	5	24	$1^{25}/_{64}$+15H	5304	$1^{25}/_{64}$+30M	8320	5304	8320
3A	1185	8	12	8	$1^{25}/_{64}$+15M	264	$1^{25}/_{64}$+30M	1856	264	1856
4A	1151	2	5	5	$1^{25}/_{64}$+15M	2784	$1^{25}/_{64}$+30M	5476	2784	5476

NOTE: H indicates hard; M indicates medium.
+15, +30 denote plus 0.015 in. and plus 0.030 in., respectively.

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Fig. 7. Cups were tested to determine the advantage of adequate stitching and vulcanizing

hold the material together firmly. Some makes of cups are stitched in addition to being vulcanized, and these cups are to be preferred inasmuch as the stitching assists in holding the cup together if subjected to a tearing action and prevents particles of the cup from being left in the hole.

At this point it might be wise to caution against the use of a cup containing copper mesh or other metal throughout the entire cup. Cups have been manufactured having copper mesh between the plies with the idea that longer life will result. This metal layer defeats the purpose of the cup as it tends to make the cup too rigid, thereby lessening its opportunity to expand properly on the upstroke of the valve. Test runs verified this, and cups of this design were discarded.

In order to test cups of different makes under similar conditions, two cups of each of six makes were placed in containers of oil and boiled for a period of ten hours. All temperatures were maintained constant, and the action of the hot oil was noted. No great difference was observed in the effect on the cups during the first two hours. All cups expanded as was to be expected. The cups were kept at boiling temperature (of the oil) until no further action was noted. The final results clearly show, however, that some makes of cups do not respond to severe treatment as satisfactorily as others. This test was conducted not as a comparison of actual field conditions but as a check on the durability of the construction of cups of different makes. In Fig. 6 the cups in the top row are shown after boiling as compared to the original cups before boiling (shown below). Cups B and F show lack of proper vulcanizing and Cup E shows some distortion. Cups A, C, and D indicate better durability under severe conditions and should give better service.

Pool A

Pool A was selected for test purposes as its characteristics were typical of shallow depth production. Well depths ranged from 950 to 1300 ft., the gravity of the oil was opproximately 30° A.P.I., and the oil contained very little floating sand. Prior to the tests, hard cups had been used exclusively throughout the pool on the traveling valves, presumably on the theory that the harder the cup, the longer the wear. It was believed that the fluid column in these wells was not of sufficient weight to expand a hard cup properly so cup replacements as the test began were made with medium hardness cups where hard cups had been used before. Experimental work was done also in determining the correct oversize cup to use during the course of replacements.

Table 2 illustrates the longer life obtained by substituting medium hardness cups for hard cups. This is more clearly emphasized when it is realized that the hard cups were installed in new working barrels and had the benefit of close tolerances whereas subsequent installations of medium hardness cups were made in barrels that had been subjected to previous wear and the medium hardness cups had to adapt themselves to the altered internal diameter. To further illustrate this point, some wells were tested with alternate installations of hard and medium cups to determine if these results were consistent. Table 2 shows that when a run with hard cups followed a run during which medium cups had been installed, and resulted in a shorter life for the hard cups, the longer length of service could be regained by again using medium cups. These tests bear out manufacturers' contention that wells pumping at depths of 1250 ft. and having average severity should use medium cups for effective seal and longer life.

The effect of tolerance in both working barrel and cups has been previously pointed out, and a study of Table 2 shows that regular size cups do not give the service in initial settings as do the plus 15-thousandths cups. Furthermore, it is illustrated in Table 3 that the actual field results obtained from using oversize cups confirm the fact that proper care must be taken in selecting the correct oversize cup to obtain maximum efficiency. The four wells shown were selected from a large group in which the bottom-hole equipment had been in service for some time. So far as it was possible to determine, no damage had occurred to the working barrel other

TABLE 4

POOL B

Comparative Service Record of Oversize vs. Regular Cups

Well no.	Well depth, ft.	Daily production, bbl.		Pumping time, hr.	First run		Second run		Third run		Fourth run		Average life	
		Oil	Water		Type	Hours service	Type	Hours service	Type	Hours service	Type	Hours service	Hard cups	Medium cups
1B	2275	20	0	18	1 25/64+15H	4914	1 25/64H	558	1 25/64+15H	1872	1 25/64+15H	2070	558	2952
2B	2335	6	2	10	1 25/64+15H	1704	1 25/64H	180	1 25/64+15H	2370	1 25/64+15H	960	180	1678
3B	2428	3	1	7	1 25/64H	78	1 25/64+15H	2130	1 25/64H	234	1 25/64H	138	150	2130
4B	2330	14	0	24	1 25/64H	552	1 25/64+15H	7320	1 25/64+15H	4650			552	5985
5B	2195	2	0	4	1 25/64+15H	356	1 25/64H	228	1 25/64H	176	1 25/64+15H	300	202	328
6B	2342	2	1/2	4	1 25/64H	272	1 25/64+15H	4800	1 25/64H	180	1 25/64H	232	228	4800
7B	2125	6	0	8	1 25/64+15H	2056	1 25/64H	224	1 25/64H	320	1 25/64+15H	1312	272	1684

NOTE: H indicates hard; M indicates medium.
+15, +30 denote plus 0.015 in. and plus 0.030 in., respectively.

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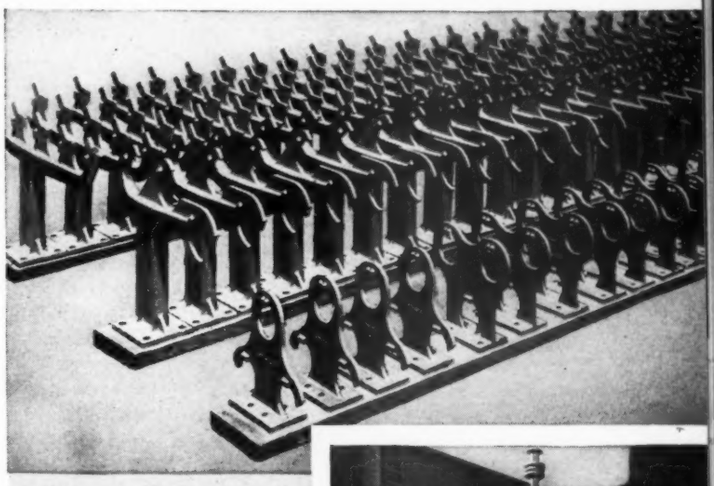

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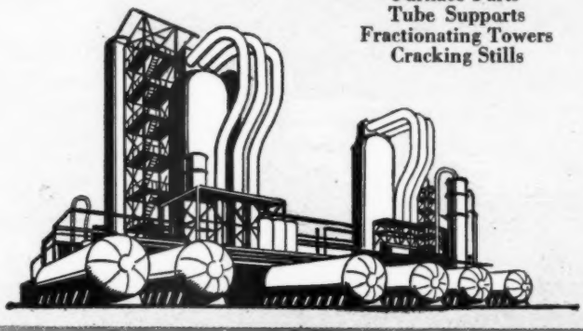

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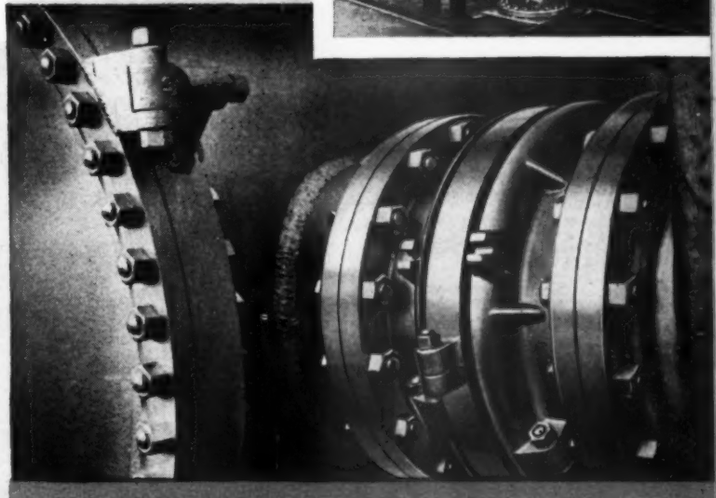

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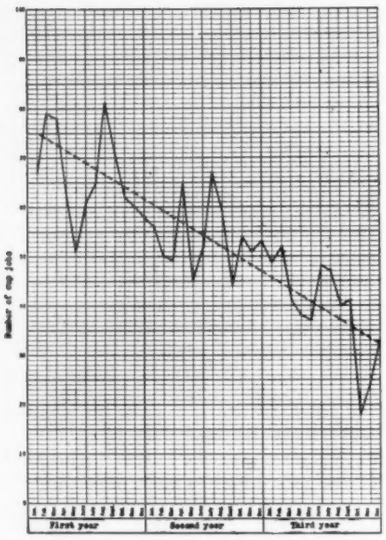


Fig. 8. Illustrating the reduction in cup replacements made possible in Pool B as a result of proper cup selection

than the normal amount of wear that was to be expected. The cup size in these four wells was changed to plus 30-thousandths to compensate for the wear (plus any tolerance), and the results in each case showed a high percentage gain in length of service. These results illustrate that the frequency of cup replacements and the wear on the equipment should be noted so that proper cup sizes should be used. These figures bear out the contention that in order to compensate for additional wear plus 15-thousandths cups should be used in new or semi-new barrels to provide for tolerances and plus 30-thousandths in barrels that had been in use for some time.

The use of medium hardness cups brought forth a new problem. These cups, not having the rigidity of the hard cups, had a tendency to reverse themselves when the traveling valve was pulled from the well, causing the valve and cups to simulate the action of a tubing swab. This would result in the loss of fluid in the tubing string, and in some cases the cups would tear, with part of the cup being left in the hole to become lodged between a ball and its seat later and cause leakage. To correct this disadvantage several remedies were advanced and tried, but none was entirely successful. The first step was to use only cups that were stitched in addition to being vulcanized. This reduced the danger of losing part of the cup if it did turn when coming out of the hole. In determining the proper cup to use for satisfactory resistance to destruction when pulled from the well, the cups shown in Fig. 7 were tested to emphasize the advantage of a stitched cup. The cup marked A in Fig. 7 illustrates a non-stitched cup after removal, showing that part of the cup was left in the hole. Cup B is a non-stitched cup that was properly vulcanized, and although it was torn during removal, it had a tendency to resist complete destruction and only a small part of the cup was left in the hole. On the other hand, Cups E and F were poorly vulcanized in addition to not being stitched. Due to the lack of proper heat treatment, these cups came apart at the plies and left large pieces of material in the hole. Cup C in Fig. 7 was both stitched and correctly vulcanized with the result that all of the cup was removed. Cup D is a hard cup used to determine whether harder cups could be used to eliminate the tearing action occurring on the medium hardness cups. Although the cup did not turn when pulled, its useful life was short due to the fact that it never expanded properly and became fluid-cut rapidly. This action is illustrated by the deep gash down the side of the cup. It was then realized that medium hardness cups should be used and that stitched cups were to be preferred over non-stitched cups.

This stitching, however, did not prevent the cup from turning, and several other methods were employed in an endeavor to eliminate this undesirable feature. Some success was had by using two medium hardness cups in the center flanked by two hard cups on the top and bottom. Although this was found to correct the situation somewhat, the few trials indicated that the length of service of the assembly was reduced inasmuch as the hard cups failed to expand properly, and the resulting action was in the nature of a two-cup valve. Better results were obtained by running the top cup of the inverted bevel type, but still of medium hardness. This permitted the cup to expand properly, and yet the lack of the sharp bevel at the top of the cup eliminated the turning of the top cup as a result of its catching on protrusions. None of the abovementioned methods produced entirely satisfactory results, and it was believed that the problem might be solved by incorporating a steel or metal ring in the cup itself, thus preventing the cup from turning yet allowing it to flex sufficiently to obtain a good seal.

As a further precaution against pieces of torn cups entering the traveling valve and lodging between its ball and seat, perforated type cages were used on the traveling valve and their use in many cases eliminated an unnecessary pulling job.

Pool B

Pool A having been selected for normal operating conditions, Pool B was chosen as one where reservoir conditions made maintenance of bottom-hole equipment difficult. This pool was developed during the period of early rotary drilling, and "boom" conditions existed. Consequently many of the holes were not properly cleaned-out on completion. Also poor cement jobs permitted rotary mud to enter the hole from behind the casing. Nearly every well in the pool had an accumulation of mud on the bottom, and it was not uncommon to pull pumps and find that they had been completely submerged in mud during operation. The wells averaged approximately 2300 ft. in depth and the fluid level was low. Gravity of the oil was approximately 32° A.P.I. with the wells making some water associated with the oil. The producing horizon was a thick bed of fine sand that sloughed readily, and the sand was suspended in the oil as floating sand. Pumping would agitate the mud and sand, and the resultant abrasive action would readily cut-out the cups. Some of the wells in which this condition was most severe were equipped with metal liner pumps to relieve the situation. As the wells were of the stripper class, however, and it was desired to hold operating costs to a minimum, tests were made to see whether the additional expense

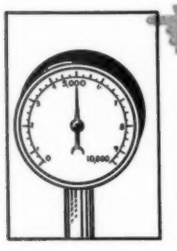
TABLE 5

Cup Service in Pool B
Two-Year Period

Year	Size cup	No. of cup jobs required	Total service for all jobs, hr.	Average life per set of cups, hr.
1st	$1^{25}/_{32}$ A.P.I	190	127,130	669
	$1^{25}/_{32}$—15 A.P.I	266	200,006	752
	Total of all jobs for first year	456	327,136	718
2nd	$1^{25}/_{32}$ A.P.I	106	84,370	795
	$1^{25}/_{32}$—15 A.P.I	214	189,961	888
	Total of all jobs for second year	320	274,331	857
	Percentage reduction in jobs	29.8		
	Percentage increase in hours service	19.4		

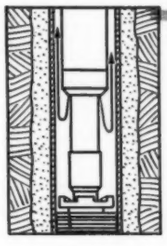
YOU DON'T HAVE TO KEEP YOUR FINGERS CROSSED When Doing a Squeeze Job with a BAKER CEMENT RETAINER

When you're doing an important squeeze job, it's a mighty good feeling to know that the tool you ran in the hole will do its work and do it properly. That's why superintendents who have the responsibility of seeing that squeeze cement jobs turn out successfully like to run Baker Cement Retainers. When a Baker Cement Retainer is on the job, they are sure of three important things:



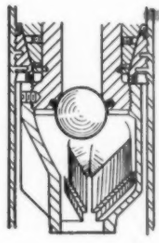
1

That the cement can be put away at the necessary pressures, and the Cement Retainer will remain securely set and packed off.



2

That fluid can be bled off (through the Circulation Joint) at any time during circulation or cementing operations.



3

That after the cement is put away, the Ball Back-Pressure Valve in the Cement Retainer will hold the pressure and prevent any return movement of fluid through the Retainer.

NOT AN EXPERIMENTAL TOOL

It is important to realize that the Baker Cement Retainer is in no sense an experimental tool . . . it has been used successfully in thousands of oil wells in fields throughout the world. The original Baker Cement Retainer was invented (and the name "Cement Retainer" originally coined) some 30 years ago, and the present tool embodies the knowledge and experience gained during that time in both manufacturing and running many Cement Retainers.

It is in this accumulation of skill and experience that goes with every Baker Cement Retainer run into the hole today, and is the reason why . . . *you don't have to keep your fingers crossed when a Baker Cement Retainer is doing your squeeze job.*

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BAKER CEMENT RETAINER

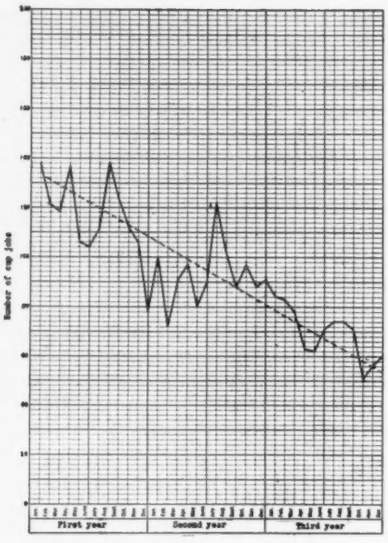

Fig. 9. Overall results obtained in several pools by studying cup performance

of more costly pumps could be eliminated in a great number of cases.

Average well depth being below the recommended depth for medium cups, testing was conducted principally with hard cups. The first group of tests was to determine the proper cup sizes, similar to the work in Pool A. Data shown in Table 4 reflects the wisdom of using oversize cups as pointed out before. These increases were so great and so consistent that there can be no doubt as to the value of this work. Based on these results, regular size cups were discontinued except in cases where the weight of the pull rods offset the weight of sucker rods to such an extent that the additional frictional drag of the oversize cups would not permit the valve to drop readily in the barrel. In some cases where 30-thousandths oversize cups were used, the length of service was not what had been expected. This group of wells was studied, and it was found that all the wells were part-time pumpers. In wells where the pumping was continuous, the expected life was obtained. Further study revealed that where wells pumped part time the finely suspended sand was permitted to settle-out when the pumping agitation ceased. This accumulation of sand would occur above the traveling valve, and during the first few strokes when pumping would be resumed, this accumulation of sand would rapidly cut the cups and score the barrel. A complete study of all part-time pumping wells against full-time pumpers revealed that the life of cups in these installations was consistently lower, but was still much greater than when regular size cups were used.

Table 5 is illustrative of the results obtained by proper care in installation of valve cups. These records cover a group of selected wells where the same grade and size cup was in continuous use for a two-year period. These data show beneficial results for the second year with a 30 percent decrease in number of cup replacements and a corresponding 20 percent increase in length of service. This was principally a result of careful installation rather than proper selection, although in a few instances oversize cups were substituted for regular cups where obviously flagrant misuse was noted.

As a further illustration of the beneficial results obtained over a 3-year period of not only careful cup installation but also of proper cup selection, Fig. 8 is a graphical representation of the reduction of cup replacements. It will be noted that continued reduction was obtained as more wells required repairs and that at the conclusion of the 3-year period, cup replacements were reduced by half. Not all this can be attributed to cup selection as some 20 of the 200 wells were abandoned, and in cases where severe sand cutting existed, metal plunger pumps were installed. This can indirectly be credited to the cup study, however, as on the basis of these findings the uneconomical wells were plugged and the severe cases were corrected with proper type metal plunger pumps.

Summary of All Tests

During the testing in Pools A and B, similar tests were being conducted in other pools. The results obtained elsewhere duplicated the data presented in the studies of Pools A and B. Fig. 9 shows that the results obtained gave approximately 60 percent reduction in cup jobs over a 3-year period. This substantial reduction of 80 cup jobs per month was immediately reflected in lower lifting costs and made it possible to continue to produce many wells and leases that otherwise would have been classified as non-commercial. The only additional fact found that has not been previously presented was that tight emulsions caused by fluid bypassing the harder and undersized cups were reduced greatly, and the oil-water separation was effected more readily.

It was found that distinct advantages result from proper cup usage. It is possible to increase oil reserves by eliminating premature abandonment of small producers where excessive cup jobs or the added cost of high-priced pumps would dictate their abandonment. The elimination of frequent cup replacements permits a reduction in the number of workmen and the amount of equipment required to make the installations, thereby reducing direct expenditures. Finally, production lost while a well stands idle waiting on pulling equipment is reduced to a minimum, and in some cases offset drainage is eliminated.

Conclusion

Based on the results of the tests the following recommendations are offered:

(1) The traveling valve, barrel, and other bottom-hole equipment should be in first-class mechanical condition.

(2) Cups should be soaked in oil either before running or allowed to set in the fluid at the bottom of the hole a sufficient length of time to absorb the oil.

(3) Records of cup runs should be available to rod crews so that previous runs might be studied and new installations made in cup sizes indicated by the records. As a general rule, plus 15-thousandths are best adapted to new or semi-new barrels, and plus 30-thousandths to old barrels.

(4) Medium hardness cups give much greater service in wells having maximum depths of 2000 ft. Greatest drawback of medium hardness cups is their tendency to turn when pulled from the well.

(5) Stitched cups and cups having reinforced shoulders are recommended.

(6) No new design has yet been developed to cause any radical change in the standard make of cups. Deep bevels, inverted bevels, and copper wire between the plies show disadvantageous rather than beneficial results.

Petroleum Employees Safest When Working

Oil-company employees in 1940 sustained only a little more than half as many fatal injuries while on duty as they did when not working, a review of fatalities by the American Petroleum Institute's Department of Accident Prevention reveals.

The 1940 fatal-injury record of the petroleum industry was the lowest since data has been reported, H. N. Blakeslee, director of the department, reported, and was 49 percent below the fatality rate in 1930.

Oil companies employing 327,112 workers reported 101 fatalities last year, or a rate of 30.9 per 100,000 workers. Off-duty fatalities of oil-company workers, reported for more than two-thirds of these employees, were almost twice as high as the industrial fatalities. The rate per 100,000 employees for those reporting both industrial and off-duty fatalities was 28.3 while on duty, compared with 48.3 while off duty.

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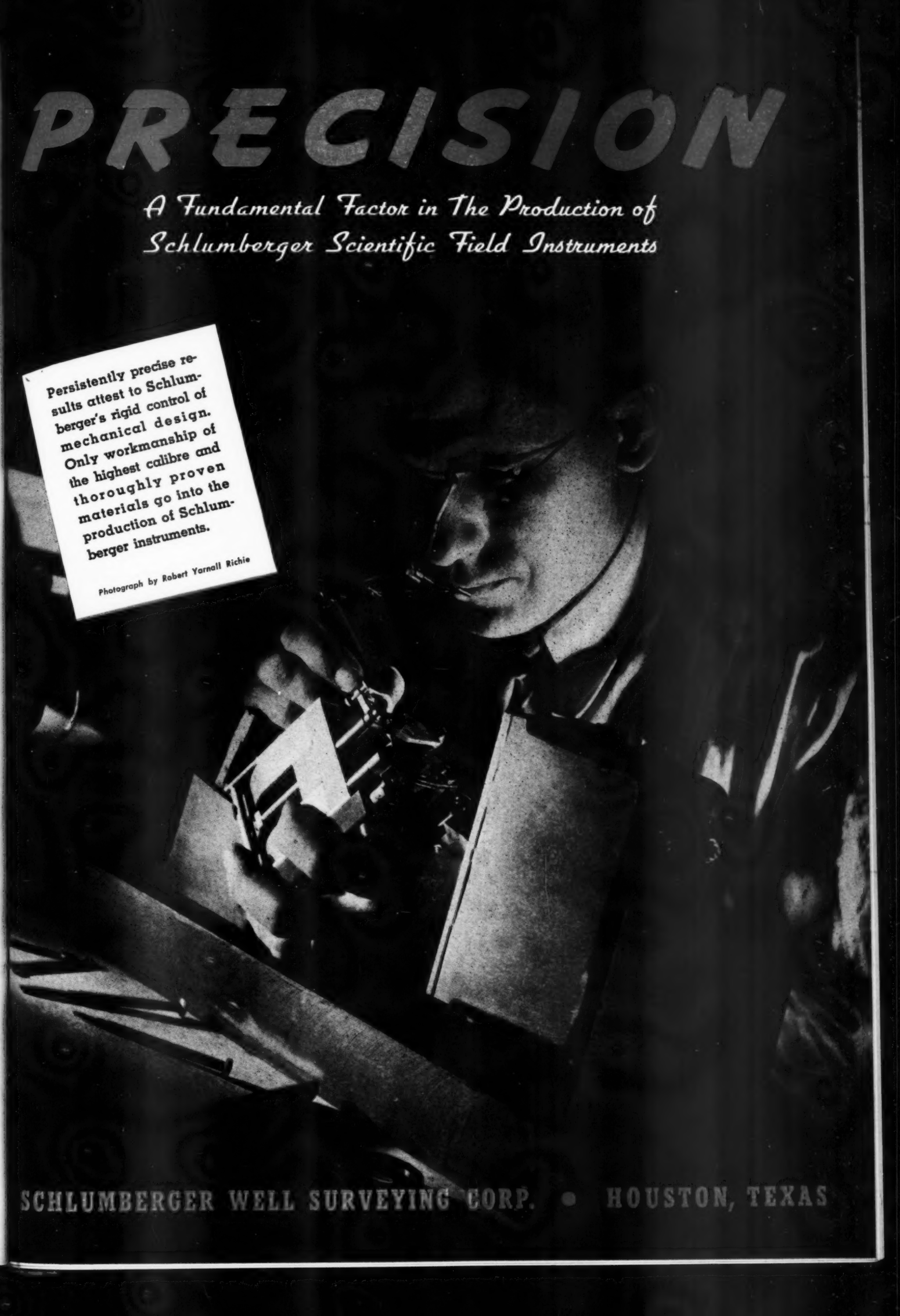

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Practical Maintenance Problems in Diesel Combustion Systems

PETROLEUM ENGINEER Exclusive Feature

☆ Attention is called to the various factors that contribute to inefficient combustion—Means of correcting various troubles are outlined

by E. R. Spencer

Engineering Department, The Cooper-Bessemer Corporation

E. R. SPENCER

After several years of teaching at Texas A. and M. College, Spencer joined the engineering organization of The Texas Pipe Line Company and affiliated companies in 1929 as maintenance engineer, and in 1936 was placed in charge of The Texas-Empire Pipe Line Company engineering office in Tulsa, Oklahoma—Since January 1, 1941, he has been with the Cooper-Bessemer Corporation in charge of turnkey power plant construction—He received a B.S. degree in mechanical engineering from the State College of Washington—Post-graduate studies were pursued while teaching at Texas A. and M. and he was awarded a professional degree from his Alma Mater in 1940 —For the last several years he has been active in the A.S.M.E.

FOR many years the heavy-duty, slow-speed, air-injection, Diesel engine was very popular and, as a result, there are many of these engines in service. Inasmuch as the injection system is rather simple and operating pressures are relatively low, it is particularly adaptable to the use of cheaper grades of fuel. Despite its simplicity and adaptability, however, the air-injection system does present certain maintenance problems. Whenever moving parts are subjected to the flow of fluids under varying pressures and high temperature, maintenance difficulties may be expected.

It is not the purpose of this article to criticize any particular product but rather to discuss the effect of normal wear, adjustments, and other operating conditions on combustion. The ensuing remarks are based, therefore, on the assumption that the individual machine parts have been properly designed and the engine, in its original condition, meets all requirements for proper combustion. Before going into the more practical details of combustion, it might be well to review briefly the thermodynamic principles involved in the Diesel cycle.

The pressure-volume relationships of a Diesel cycle are shown in Fig. 1. The curve AB represents the condition of the combustion of air as it is adiabatically compressed. Section BC represents the period of fuel injection that, in practice, approaches constant pressure. CD indicates adiabatic expansion of the gas, which drives the piston downward and thus increases the cylinder volume. At point D, the exhaust opens to atmosphere and the constant volume pressure change takes place down to point A, thus completing the cycle.

The coördinates used to describe the process of the Diesel cycle are pressure, volume, and temperature. Thus $P = F(V, T)$, where P = lb. per sq. ft. absolute, V = volume in cu. ft., T = absolute temperature, °F.

The fundamental relationship of these conditions is found from a combination of two general gas laws known as Boyle's Law and Charles' Law. Boyle's Law states that when the temperature remains constant, the volume of a given weight of gas varies inversely with the pressure. Thus,

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}, \text{ or } P_1V_1 = P_2V_2 = P_3V_3 \ldots = P_nV_n = \text{constant} \quad \text{Equation (1)}$$

Charles' Law states that:

(1) With constant volume the pressure of the gas change is directly proportional to the change in temperature,

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \quad \text{Equation (2)}$$

(2) With pressure constant the volume of gas varies in direct proportion to the temperature change,

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \quad \text{Equation (3)}$$

A combination of these laws results in the following equation:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \ldots = \frac{P_nV_n}{T_n} = \text{constant} \quad \text{Equation (4)}$$

The above laws completely describe the condition of the so-called constant pressure and constant volume changes.

During adiabatic changes, the volume increases against resistance, that is, during adiabatic expansion with the doing of external work—the temperature of the gas must decrease because external work is done at the expense of sensible heat. During adiabatic volume decrease—adiabatic compression—the temperature must increase because the heat equivalent of the work of compression goes to increase the sensible heat of the gas. Obviously, in this imaginary operation, the heat that disappears during expansion equals the external work done; and during compression the work of compression equals the heat increase in the gas.

Inasmuch as, during an adiabatic process, the supply of sensible heat, and hence also the temperature, is constantly changing—decreasing during an expansion and increasing during a compression—it is necessary to find some means of determining the extent of this temperature variation.

Without taking time to develop the intervening steps, the following equation describes the thermodynamic conditions of a gas that is changing adiabatically:

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad \text{Equation (5)}$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} \quad \text{Equation (6)}$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{Equation (7)}$$

The symbol γ in the equations represents the ratio of the specific heats of a gas at constant pressure and constant volume.

Perhaps the best way to determine combustion condition is by the use of a pressure-volume indicator. The most useful form of indicator card for studying combustion from a practical standpoint is what is commonly called the 180° or pull card. On these

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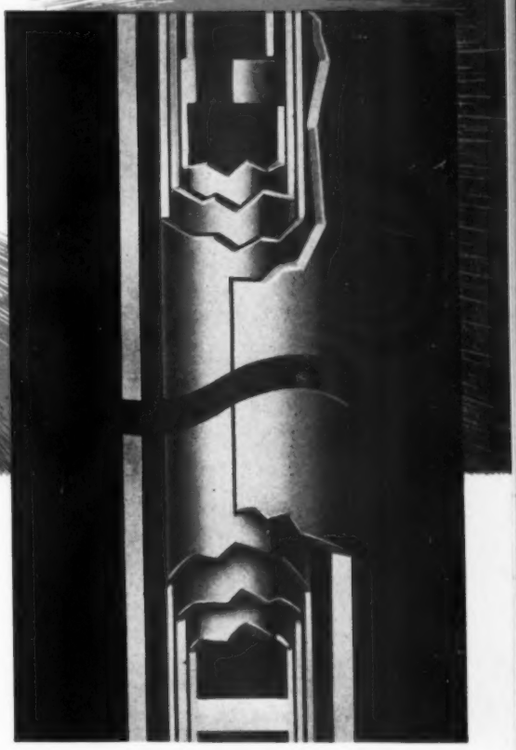

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cards the controllable operations are drawn out more than is possible on the power cards. An accurate pull card gives an excellent picture of the pressures in the cylinder during compression, injection, and expansion without respect to volume changes. The methods used in procuring these cards need not be discussed here, other than to say that it is important to obtain accurate cards without distortion caused by pencil vibration, sticking plungers, etc.

Pull cards taken at proper intervals during the process of repair and adjustment will greatly assist in determining the remedial steps that should follow.

There are many requirements that are essential to good combustion. To begin with, there must be sufficient air (by weight) present in the cylinder to supply oxygen necessary to produce complete combustion of the fuel.

The inert gases of combustion, then, must be expelled and a fresh charge of air taken into the cylinder prior to the beginning of compression. Obviously, the most important engine parts that control the scavenging of dead gases and intake of fresh air are the exhaust and intake valves. Both of these valves, then, must function properly, and as the manufacturer intended, if the required air supply is to be present for compression and ultimately for combustion. From a study of the operating sequence of these valves, it becomes evident that their opening and closing, with respect to other operating mechanisms, are very important. If the exhaust valve closes too soon, or has insufficient lift, the cylinder is left partly filled with inert gas. On the other hand, if it closes late, injection air will escape. In like manner, for example, if the intake valve closes early, the cylinder volume is only partly filled with fresh air. A review of the operating sequence of these valves will show that any distortion will finally result in a deficiency of combustion air.

The timing of exhaust and intake valves is largely controlled by the cam

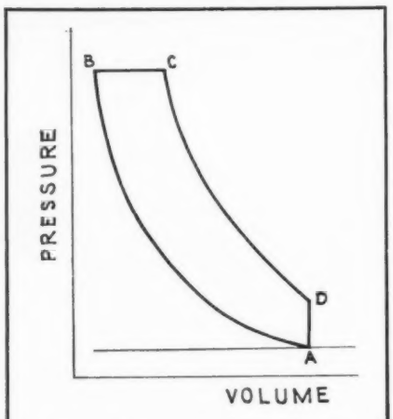


Fig. 1. Pressure-volume diagram for Diesel cycle

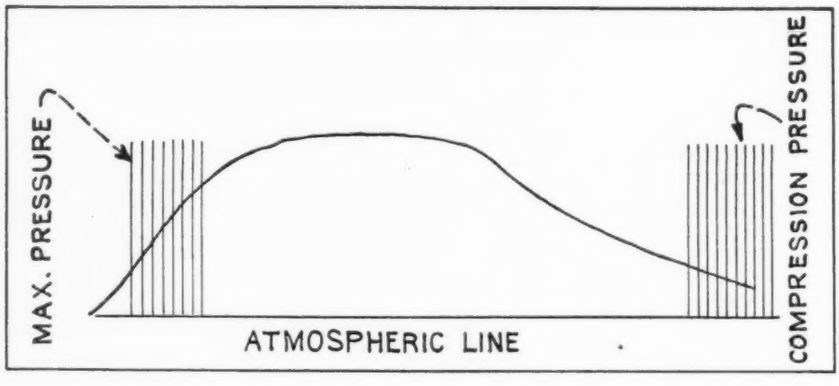
nose position, with respect to cylinder volume changes that, in turn, are dependent upon crankshaft position. The cam roller clearance also affects valve timing. The main difficulty, however, arising from excessive roller clearance is the reduction of valve lift and retardation of the time of opening. The truth of the above statement is apparent and needs no comment.

Occasionally the cause of insufficient combustion air is found outside the engine itself. Clogged air filters, restricted air passages, etc., often cause trouble.

With the required weight of air in the cylinder, it is necessary that it be compressed to the proper pressure. The reason for this compression is twofold:

First, by definition of the Diesel cycle, it is necessary for the fuel to be injected into an atmosphere having a temperature sufficiently high to ignite it. When the initial charge of air in the cylinder is suddenly reduced in volume, there is little heat transferred through the cylinder walls, and the temperature is, therefore, increased. According to the fundamental theory, this constitutes an adiabatic compression, which is described by Equation (5).

Fig. 2. Typical pull card



Second, it has been found that when fuel oil is sprayed into a high-temperature atmosphere the resulting flame propagation is approximately proportionate to the proximity of oxygen molecules. That is, when the oxygen molecules are compressed close together by high pressure, the flame travels rapidly and evenly. The fundamental adiabatic equation (6), involving pressure and volume, indicates that this high pressure is attained when the volume of gas changes without the loss of heat, as outlined above.

A casual study of these equations shows that a compression ratio of approximately 16 to 1 will, under normal conditions, produce the required temperature and pressure.

The exact compression ratio, however, is determined by each individual manufacturer; thus, the clearance between the cylinder head and piston has a very definite value. It is important to maintain the specified clearance volume if the required weight of air is supplied for combustion at a designated pressure.

In practice it is extremely difficult to determine accurately the temperature in an internal-combustion engine in a direct manner. On the other hand, it is a relatively simple matter to procure accurate pressure readings. Thus, if the pressure is determined, the temperature can be readily calculated by Equation (7).

Fig. 2 shows a typical indicator card bearing the information commonly used in combustion system maintenance. The series of vertical lines on the right represents the compression pressure for several strokes of the engine. For purpose of discussion, assume that the lengths of these compression lines vary, that is, the compression pressure is less on some strokes than on others. The principal cause of this condition is sticking head valves. A card, taken after the valves have been lubricated, and uniform compression pressures have been assured, will indicate the true value of compression. If it is found to be below that recommended, the cause must be located and corrected. In addition to the maladjustment discussed above, there are a number of practical causes for low compression, such as:

(1) Blow-by
(2) Insufficient cam roller clearance on exhaust and intake valves allowing them to remain partly open
(3) Leaking exhaust and intake valves
(4) Fractures in cylinder head, piston head, etc.

Time does not permit a detailed discussion of the above factors, individually. It might be said, however, that

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the procedure in determining the exact cause and correction of low compression will, to a large extent, depend upon the particular engine involved.

Excessively high compression will result in undue pressures and so-called rough burning. The cause for this high compression can usually be found in erroneous clearance volume adjustment.

With proper scavenging and good compression, we leave that part of the cycle represented by DAB, Fig. 1.

The constant pressure and adiabatic expansion portion are so dependent upon each other that they must be considered together. These are represented by BCD, Fig. 1.

As previously pointed out, the portion of the cycle represented by BC, Fig. 1, is that of fuel injection. Obviously, if there were no fuel injected at the end of the compression stroke there could be no constant pressure portion, but an adiabatic expansion would be superimposed on the compression curve during the outward stroke of the piston. From the fundamental equation and by definition, $P_1 = P_2 =$ constant, then,

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \text{ (Equation 3).}$$

Thus, if the volume is to increase, the temperature must also increase provided constant pressure is maintained. In other words, the volume and temperature will vary in a definite, direct ratio. The only source of heat supply during this constant pressure change is from the burning of fuel. Without further consideration, the principle governing the injection portion of the Diesel cycle can be stated: *Fuel must be injected at a rate and time such that the heat liberated by its oxidation will provide the heat required to maintain a constant pressure while the volume changes at an increasing rate.*

Each engine manufacturer has developed his own means of introducing the fuel at the proper time and required rate. As it is impossible to discuss each injection system, remarks will be confined to typical types and a few very common maintenance problems.

Perhaps the most perplexing problem confronting the average Diesel operator is that of fuel. This is especially true in crude oil transportation plants. In these plants the fuel is usually poor as, in many cases, crude oil is used. The operator, therefore, has little or no control over the grade of fuel used. The problem then resolves itself to one of getting the best possible results from a certain fuel used in existing equipment under a given load and speed requirement.

One of the most common types of fuel valves and operating mechanisms is shown in Fig. 3. Only a brief glance at Fig. 3 is necessary to note the operating sequence of the mechanism.

As previously intimated, most engine builders deviate slightly from the absolute constant pressure condition.

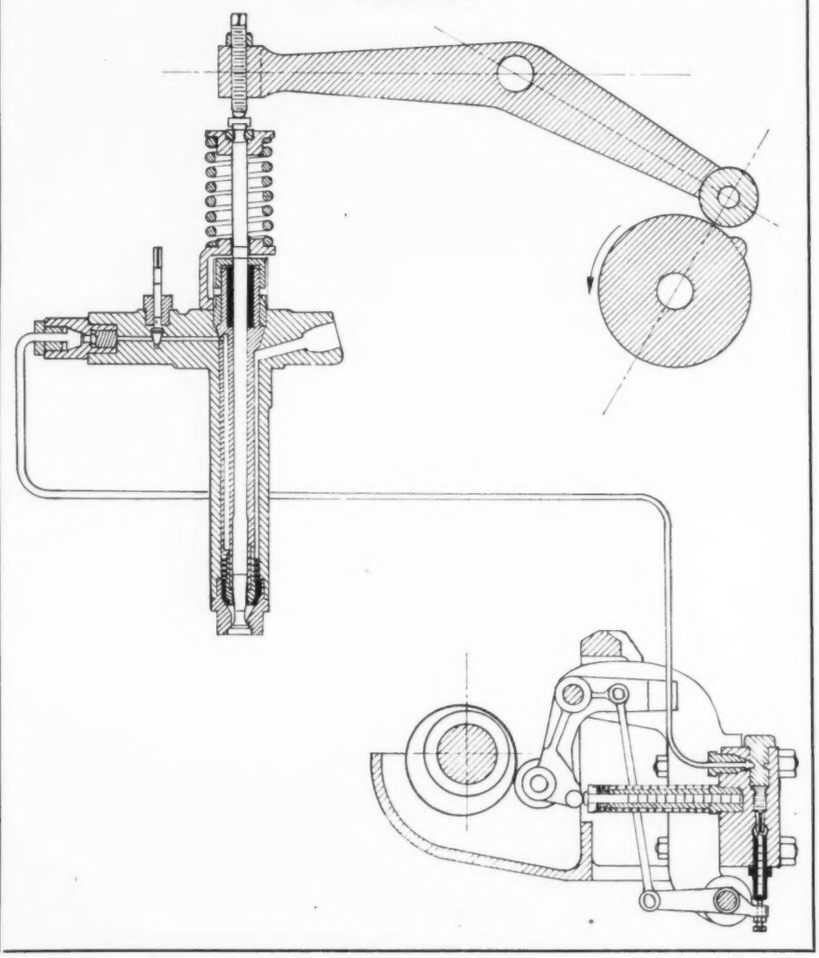
The length of the vertical lines shown on the left of Fig. 2 represents the maximum pressure in the cylinder during each cycle. The length of these lines should be uniform for the best combustion. Very often, however, these lines will be found to vary in length, indicating uneven firing pressures. This unsatisfactory condition is usually caused by a variation in the amount of fuel supplied to the cylinder. If the variation in pressure occurs gradually, the cause can normally be found in a hunting governor. On the other hand, if the length of pressure line varies from maximum to minimum without any apparent pattern, the trouble will usually be found between the fuel pump and spray valve. The fuel check valves may leak, allowing varying quantities of injection air to leak back into the fuel lines during the pump suction period. The difficulties arising from such leakage are apparent.

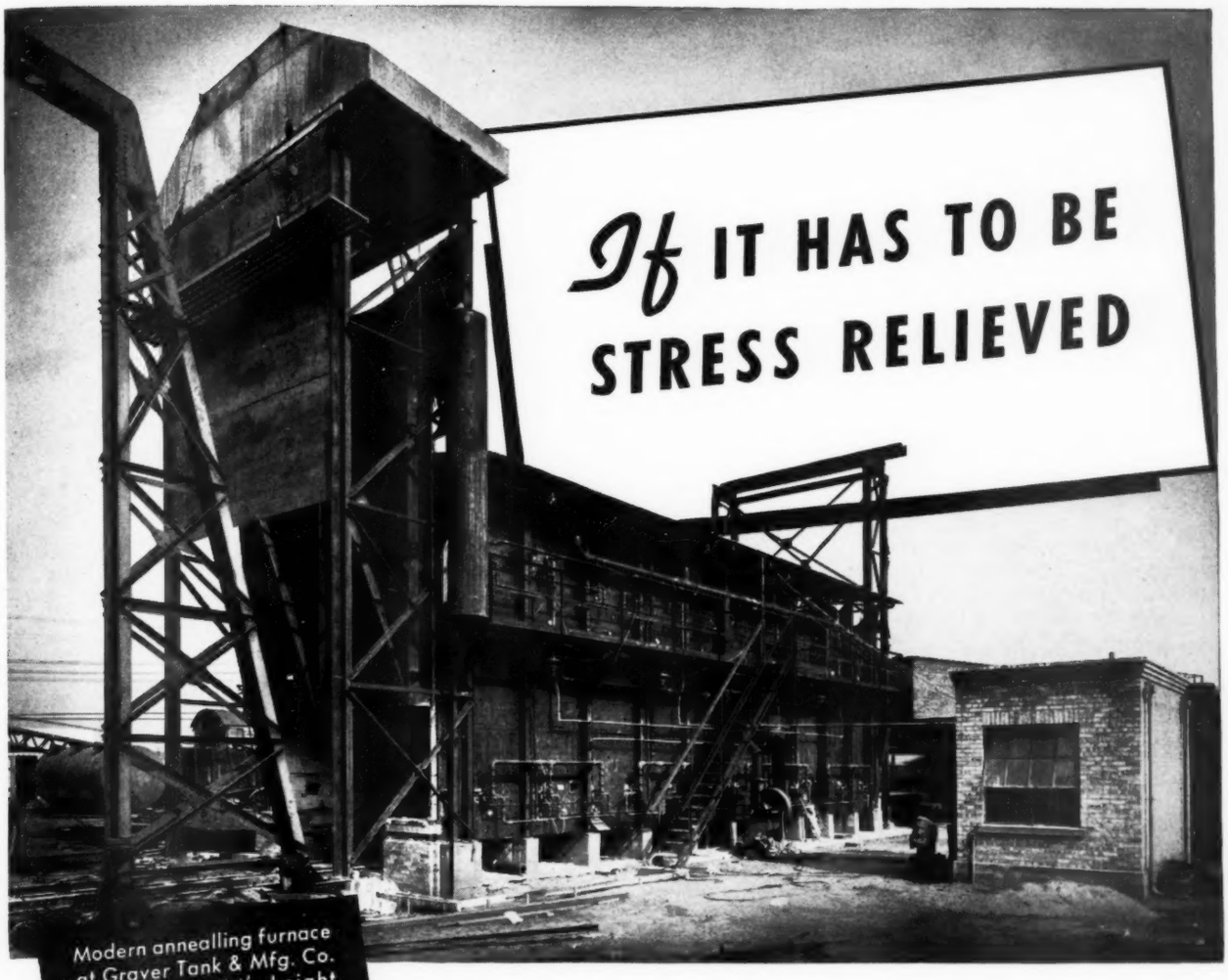
Some of the other conditions that produce erratic fuel supply are:

(1) Faulty or fouled fuel pump valves
(2) Excessive wear in fuel pump plunger driving mechanism
(3) Faulty packing
(4) Insufficient supply of fuel to pump suction.

The average value of maximum firing pressure as indicated should not be more than 10 to 15 percent greater than the compression pressure at full load and normal speed. It should be noted that this increase in pressure is the practical deviation from the ideal previously mentioned. Needless to say, the maximum firing pressure for a given fuel, load, and speed is controlled by many factors. An early opening of the fuel valve will produce excessive pressures. The reason for this is evident when the volume changes are considered. For example, if the fuel valve should open so that burning starts before the piston reaches the extreme position, then for a brief part of the

Fig. 3. One of the most common types of fuel valves and operating mechanisms





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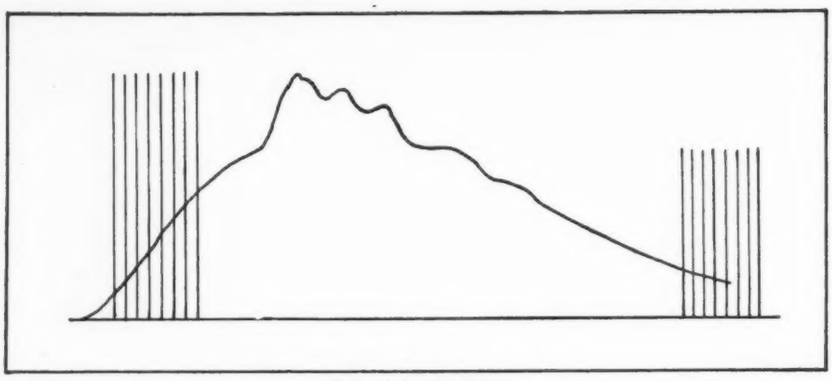


Fig. 4. Early timing

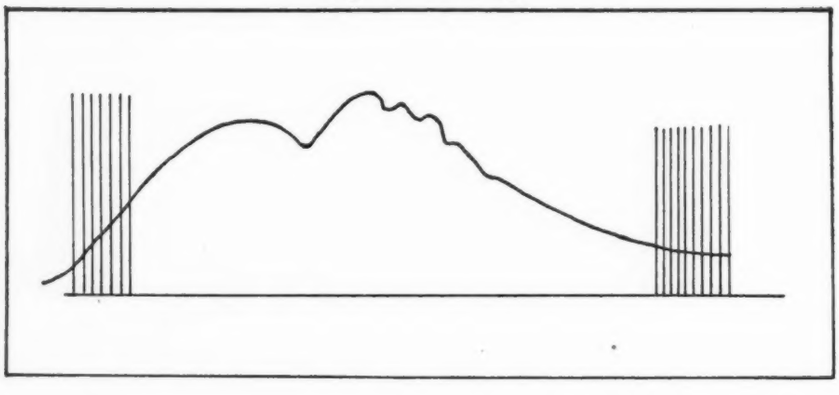
injection period the volume is actually decreased. As the crank passes the center, the piston moves very slowly and, consequently, the volume change is very slight. Obviously, the temperature of the gas will increase faster than intended, thus producing excessive pressure. By similar reasoning, it is apparent that low firing pressures will result from late firing or late valve opening.

Injection air pressure has a similar effect on firing pressure. The higher the air injection pressure the greater will be the velocity of air and fuel out of the fuel valve into the cylinder. This rush of fuel through the small passages of the fuel valve and into the combustion chamber has a tendency to increase the firing pressure in two different ways. First, the fuel enters the combustion chamber at such a high rate that heat is liberated faster than normally. Second, the high velocity through the spray valve atomizer and spray nozzle divides the fuel so finely that flame propagation and the rate of combustion are materially increased. The effect of both is to liberate heat at such a rapid rate that the pressure increases beyond the desired maximum when volume changes are slight. The converse is true when the injection air pressure is too low.

This rapid introduction of fuel results in the entire charge of fuel entering the combustion chamber during the first part of the fuel valve opening. During the remainder of the injection period, cold air blasts into the cylinder without the liberation of heat. It has been found that the chilling effect of these cold blasts often causes erratic burning, the natural result of which is sudden pressure variation in the cylinder, thus producing a wavy expansion line on the indicator card.

The importance of injection timing has already been intimated. A more detailed discussion, however, of the cause and effect of maladjustments in this regard will be of interest. Either early or late timing can best be detected by the use of an indicator card. The 180° card (Fig. 4) indicates early timing. It will be noted that the compression curve does not reach its maximum value before the fuel is injected and the pressure is increased beyond a reasonable value. This condition will, of course, cause excessive bearing pressures and unnecessary strain on the entire engine frame work. Late timing is shown in Fig. 5. The dip at the end of the compression curve indicates that the piston reached the extreme position and started to move away from the cylinder head before combustion began. This condition results in loss of efficiency, reduced power, high exhaust temperature, incomplete combustion, etc.

Fig. 5. Late timing



Either one of these timing conditions may be affected by such common adjustable features as cam roller clearance and cam location. The fuel cams on most engines are adjustable. It is, therefore, always well to check the general camshaft position relative to the crankshaft by comparing the relationship of a fixed exhaust or air intake cam to its corresponding crank throw. This done, the cam roller clearances and consequent valve lift should be determined. The degree of crankshaft rotation between the opening and closing of the fuel valve is important. Obviously, if the lift and corresponding period of opening are not what they were designed to be, the time of injection, as well as the quantity of fuel delivered, will be materially affected. If, after the roller clearance has been adjusted, there is still evidence of bad timing the position of the cam nose should be determined. In the case of early timing, the proper adjustment of the cam nose will produce satisfactory results. On the other hand, if late timing is in evidence there are several other factors that must be considered, together with cam position and roller clearance. Of course, if there is no wear, the late timing can be overcome by proper adjustments.

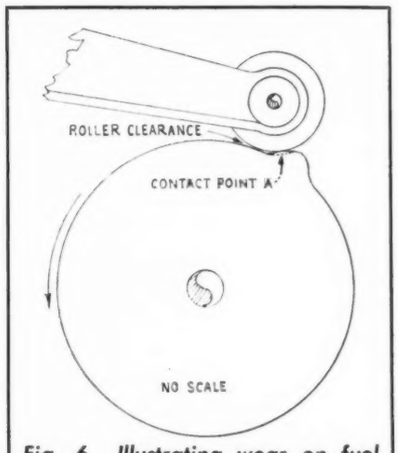


Fig. 6. Illustrating wear on fuel cam nose

Wear is one of the most difficult factors to deal with in combustion system maintenance; however, space will not permit a detailed discussion of more than two conditions of wear.

Wear at the point of contact, between the conventional fuel valve seat and the fuel needle itself, causes much trouble from a timing and firing pressure standpoint. The major cause of this excessive wear may be attributed to the following inherent factors:

(1) High spring tension
(2) Small bearing area

(3) Fuels containing abrasives and acids
(4) High velocities
(5) High temperatures

The wear on these parts distorts the relationship of the entire valve-operating mechanism. When the tip of the valve needle buries itself by wear into the valve seat, a close fitting shoulder is thus formed around the needle. Often this shoulder fits so closely that fuel will not pass to the cylinder until the needle valve has been lifted from the recess. Thus, even though all other adjustments are correct, the fuel will actually enter the cylinder too late. The charge of fuel, when finally released into the cylinder, enters at an irregular rate, which often causes high firing pressure. Under these circumstances, the burning is uneven as evidenced by a ragged injection line on a pull card. On first thought, it might appear that this condition of wear can be compensated by decreasing the roller clearance, which would tend to open the valve earlier. True, the dip on the card will tend to disappear but the increase in the rate of injection will increase the firing pressure beyond any reasonable value.

Another very common, yet troublesome, form of wear is indicated in Fig. 6. At point "A," where the roller makes contact with the cam nose, wear is quite severe. As indicated, the tendency is to retard the lifting of the roller and, consequently, the fuel valve opening. It also changes the contour of the cam itself. The height of the cam nose does not change materially; therefore, the wearing away of the low portion of the nose results in a very steep lift. Once the roller starts to lift, it reaches its maximum position almost instantly. Thus, the fuel oil rushes suddenly into the cylinder and ignites, increasing the pressure to values far greater than desired. The only practical correction for each condition is to replace the worn cam nose with a new part.

From the foregoing discussion of causes and effects of certain combustion conditions, there are several evident facts:

First, there are so many minute details involved in the maintenance of a combustion system that a catalog of each problem, with the necessary instruction for correction, is a practical impossibility.

Second, it is impossible to work accurately and efficiently with combustion problems without a fairly broad knowledge of the thermodynamics involved.

Third, the causes of improper combustion are so interdependent and involved that any given problem must be solved by a process of elimination. This process may be by mental deduction or by actual determination. In any event, a broad experience, coupled with the knowledge of fundamentals mentioned above, is the greatest asset to the solution of combustion problems.

Petroleum and Natural Gas Fields in Wyoming

THE development of Wyoming as a petroleum and natural gas producing state, from early pioneering days, through the peak year of 1923 when it was the fourth largest producer in the country, down to recent years when it ranked eighth among the oil yielding states of the Union, is described in an illustrated report completed by the U. S. Bureau of Mines.

As background to the technical descriptions and discussions of the various oil fields of Wyoming, the report provides a historical resume.

The report of the Bureau of Mines, is entitled "Petroleum and Natural Gas Fields in Wyoming," and was prepared by the Bureau in coöperation with the Geological Survey of the U. S. Department of the Interior, and the University of Wyoming. The authors are members of the staff of the Bureau's Petroleum Experiment Station, Laramie, Wyoming.

Petroleum has had an influence on Wyoming's development ever since 1847 when the Mormons, on their pioneer journey to Great Salt Lake, skimmed oil from the Brigham Young spring in the southwestern corner of the state. Four or five years later, Kit Carson and some half-breed Indian associates were packing oil on ponies from a seepage on Oil Mountain, in what is now Natrona County, to the California trail.

In 1867 and 1868, only about 9 years after Col. E. L. Drake started the American petroleum era by drilling a well to the depth of 69½ ft. on the bank of Oil Creek in Venango County, Pennsylvania, a well 480 ft. deep was drilled in the vicinity of the Brigham Young spring, but it found neither oil nor gas. From 1884 to 1886 three producing wells, ranging in depth from 200 to 750 ft. were drilled near the seepage on Dallas Dome. Some of the oil they produced was hauled with teams 125 miles to stations on the Union Pacific Railroad.

The shallowness of those early wells is in marked contrast to depths of 5200 to 5600 ft. at which oil is now being produced from the Leo sand of the Minnelusa formation in the Lance Creek field of Niobrara County. In the Badger Basin field of Park County a producing well has been completed at a depth of 8723 ft. (and a depth of 10,121 ft. was reached in deepening a well in the field in 1940).

In 1889 oil was found in the southwestern part of the Powder River Basin, east of the southern end of the Big Horn Mountains, by drilling a well about 1000 ft. in the Shannon pool. During the years 1893 to 1896 oil was hauled from the Shannon pool southward to Casper by 12- and 16-horse teams, whose drivers had no idea that they were passing over what later was to become the most prolific field in the Rocky Mountain region and one of the great fields of the world. This was the Salt Creek field of Natrona County, opened with the discovery in 1908 of oil in the First Wall Creek sand. Later the Second Wall Creek, Lakota, Third Wall Creek, Second Sundance, Third Sundance, and Tensleep sands were proved to be productive.

At its peak in 1923 the Salt Creek field produced more than 35,000,000 bbl. of oil from 907 wells. Largely because of that output, Wyoming then stood in fourth place in volume of production among the oil-producing states. It did not maintain that position, but it has continued to be an important producer. In 1940 Wyoming was in eighth place and the output of the Salt Creek field was only about one-fifth of the state's production. Hamilton Dome, Grass Creek, Elk Basin, Big Muddy, Lost Soldier, Rock River, Lance Creek, La Barge Oregon Basin, Garland, Medicine Bow and many other fields discovered since Salt Creek started to produce in 1908 have contributed importantly to Wyoming's production, but in total volume of oil produced to date, Salt Creek far exceeds any other field of the Rocky Mountain region.

Bulletin 418, Petroleum and Natural Gas Fields in Wyoming, by Ralph H. Espach and H. Dale Nichols, includes 72 illustrations, most of which are maps of the structures, and an extensive bibliography classified by fields. An appendix contains data from 104 analyses of oils, 66 analyses of gases, and 62 analyses of waters, together with tables showing oil and gas production of the individual fields by years. Copies of Bulletin 418 may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C., at the price of $2.25.

Accurate Voltage Control Is Feature of New Holiday Detector

PETROLEUM ENGINEER Exclusive Feature

☆ Operating data disclose low voltage just as effective as high for detecting voids in pipe-line coatings

by D. E. Stearns

Engineer, United Gas Pipe Line Company

DURING the last few years considerable advancement has been made in the art of protecting underground pipe lines from the effects of soil corrosion. Numerous coverings have been developed for application to the surface of the pipe to prevent corrosion of the metal in the ground and thus lengthen its useful life and minimize the necessity for repairs due to soil corrosion during that useful life. One type of covering, the so-called enamel coating having a bituminous base, must be heated to a temperature of a few hundred degrees until it attains a molten form; in this condition it may be applied to the surface of the pipe. After application to the surface of the pipe the enamel coating cools rapidly after striking the comparatively cool pipe, clinging to its surface with an appreciable thickness in a smooth, even coat. Due, however, to a number of reasons not to be discussed here, faults or holidays occur in the enamel coating that may exist as bubbles, folds, breaks, cracks, pits, thin spots, skips, carbonized particles, etc.

The principal feature of the enamel coating is its high electrical resistance inasmuch as present-day theory of soil corrosion demands that the metal surface must be insulated electrically from the adjacent soil. It is mandatory, therefore, that all faults be repaired before the pipe is considered to be perfectly covered as the rate of metal corrosion at any fault is greater when the metal around it is well coated than it would be if the metal were bare.

As it is impossible to detect all holidays by visual inspection, it has become the practice to inspect the freshly covered line by electrical means.

The Holiday Detector

Any high voltage electrical device used for the inspection of dielectric coverings after application is commonly called a holiday detector. The type now used most commonly consists of three basic units:

(1) The power unit, either batteries or other source of electrical energy.

(2) High voltage generating unit.

(3) Exploring electrode, consisting of a metal collar, usually of wire bristles, to encircle the covering being inspected.

In using this type of holiday detector the high voltage terminal is connected to the exploring electrode. The latter is passed over the surface of the covering being inspected and the ground terminal is connected to the metal under the covering in some convenient manner. When a holiday is encountered a discharge in the form of an electric spark of variable intensity occurs from the exploring electrode through the holiday to the metal under the covering.

D. E. STEARNS

is a senior engineer in the general office of United Gas Pipe Line Company, Shreveport, Louisiana—He attended Ohio State University for two years—Employed by Ohio Central Lines Division of New York Central Railroad Company four years—Re-entered O.S.U. and graduated in June, 1931, with B.S. degree in civil engineering—Entered employ of United Gas Pipe Line Company in July, 1931—Served as district engineer at several points on system—Transferred to general office in 1936—Is an associate member of Sigma Xi, and a registered professional engineer in State of Texas—Developed new detector discussed in this article.

The Electronic Holiday Detector

Acting upon the contention of V. E. Hamilton, Jr., construction superintendent of United Gas Pipe Line Company, that better holiday inspection apparatus was needed in order to provide more positive inspection and to expedite construction progress, an improved type of holiday detector has been designed and built by the writer by use of which it is believed that uniformly dependable inspection can be accomplished. By use of this detector inspection is made possible at a rate exceeding that of the pipe coating operation itself.

This newly designed instrument has been named the "Electronic Holiday Detector". The principle upon which it works is that whenever a fault is encountered in the inspection of insulating coverings, whether the discharge from the exploring electrode is readily visible or not and whether the discharge makes an appreciable noise or not, the said discharge will cause appurtenant equipment to be energized in such a manner: (a) cause a change in meter reading; (b) cause a green light to extinguish and a red light to illuminate; (c) cause a bell alarm to ring; (d) produce a registration on a counter; (e) cause a mark to be made on the pipe, and (f) to perform any other action that can be controlled electrically either directly or indirectly — all these indications occurring simultaneously. In other words, when using the Electronic Holiday Detector it is impossible to pass over a holiday in the insulating covering that causes a discharge at the ex-

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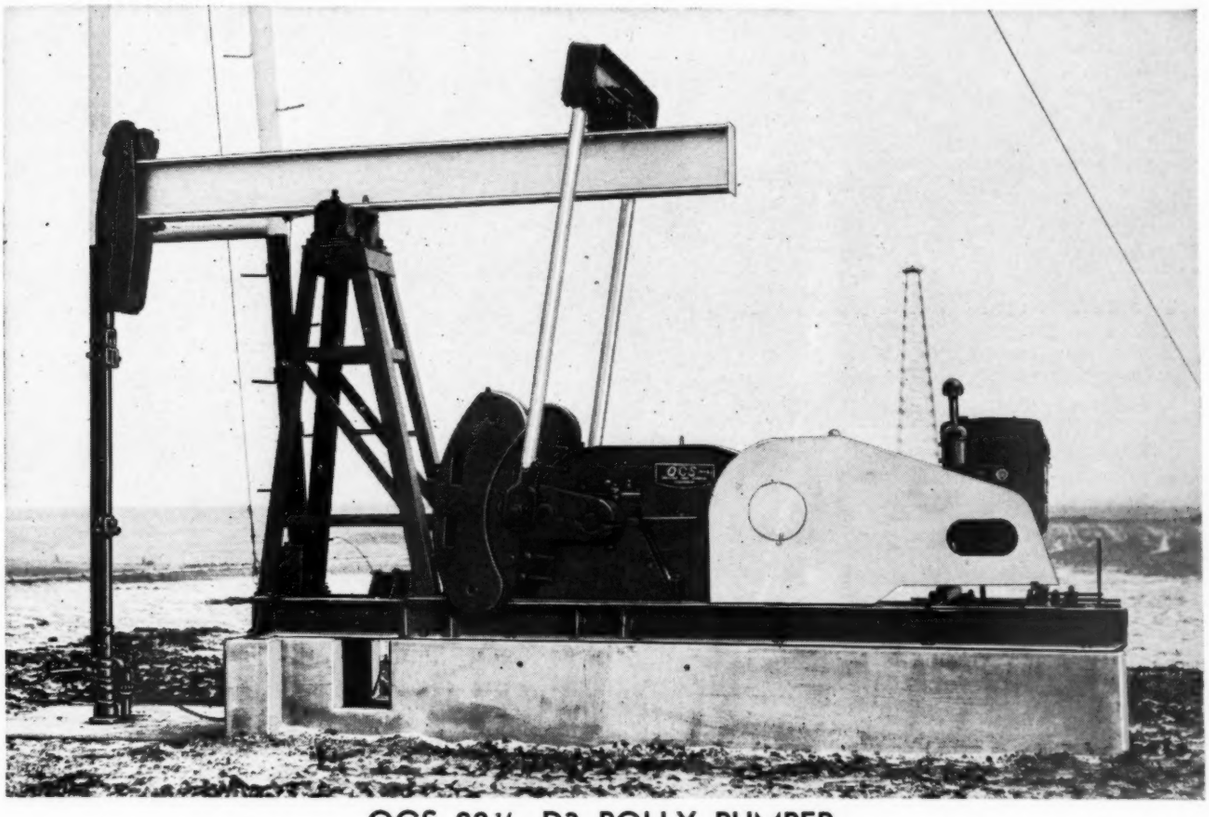

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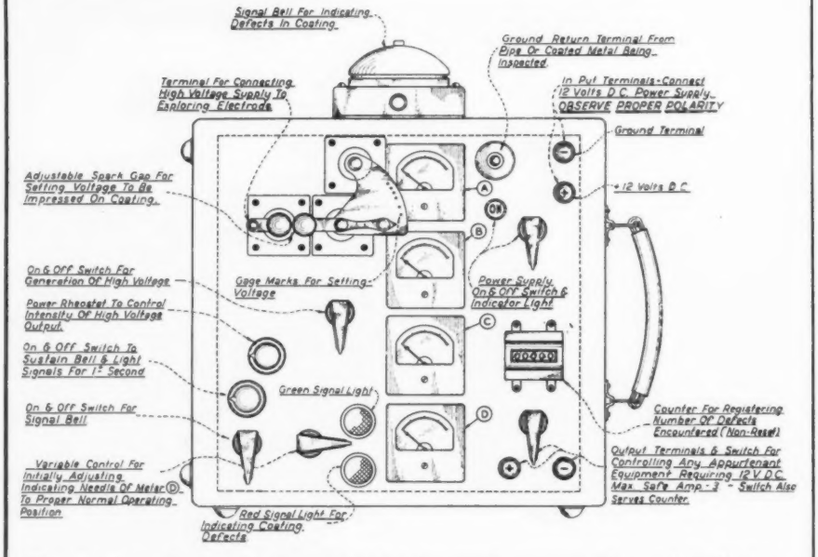
Signal Bell For Indicating Defects In Coating
Ground Return Terminal From Pipe Or Coated Metal Being Inspected
Terminal For Connecting High Voltage Supply To Exploring Electrode
In Put Terminals-Connect 12 Volts D.C. Power Supply OBSERVE PROPER POLARITY
Ground Terminal
+12 Volts D.C.
Adjustable Spark Gap For Setting Voltage To Be Impressed On Coating
On & Off Switch For Generation Of High Voltage
Gage Marks For Setting Voltage
Power Supply On & Off Switch & Indicator Light
Power Rheostat To Control Intensity Of High Voltage Output
On & Off Switch To Sustain Bell & Light Signals For 1" Second
Green Signal Light
On & Off Switch For Signal Bell
Counter For Registering Number Of Defects Encountered (Non-Reset)
Variable Control For Initially Adjusting Indicating Needle Of Meter (D) To Proper Normal Operating Position
Output Terminals & Switch For Controlling Any Appurtenant Equipment Requiring 12 V.D.C. Max. Safe Amp. - 3 - Switch Also Serves Counter
Red Signal Light For Indicating Coating Defects

Fig. 1. Top view of instrument showing various controls and indicators. (a) Voltmeter to show at all times the condition of the power supply. (b) Ammeter to indicate the amount of current being taken from the power supply. (c) Meter to indicate current flowing in the high voltage inspection circuit. (d) Meter to indicate conditions in a control circuit

ploring electrode without obtaining from the apparatus several distinct signals, all taking place irrespective of the speed at which the exploring electrode is moved over the surface being inspected. Thus a uniform and complete inspection is made possible in minimum time.

Positive Inspection

With some detectors it is difficult to distinguish the noise produced by the discharge when a holiday is encountered from other noises usually present on construction work such as that from the operation of equipment, etc. Furthermore, the actual operation of certain types of exploring electrodes, especially along wrapped pipe, produces a sound very similar to that made by the discharge when a holiday is encountered.

With most types of detector used heretofore it has not been possible for holidays to be found by the device without producing sufficient noise or light to be noticed by the operator. When blisters occur in the covering or when a holiday exists beneath the pipe-line wrapper, it is possible for the discharge to be hidden from view and its sound muffled due to the discharge taking place within the blister or beneath the pipe-line wrapper. When using the new detector all such holidays are definitely indicated.

Whereas an external dead short in the inspection circuit with the usual type of detector will not produce any crackling noise or noticeable light, the Electronic Holiday Detector functions as satisfactorily under such conditions as in instances when only a partial short circuit is developed.

Inspection by the new type detector is not dependent upon the alertness and careful attention of the operator, as a distinct and plainly audible sound as well as other indications will be produced when a holiday is encountered.

Fast Operation

It is logical that any improvements increasing the effectiveness of the holiday detector will likewise result in increasing the overall speed of the coating operation.

Most holiday detectors require that the exploring electrode be moved slowly back and forth to produce a number of discharges that will produce a sound or light of some variable intensity that may be noticed by the operator. The exploring electrode of the Electronic Holiday Detector can be moved steadily forward, as any holiday will immediately cause the operation of the indicating devices.

When the Electronic Holiday Detector is employed it is unnecessary to rely on only the brush type of exploring electrode. The improved instrument can, therefore, be used in connection with any other type of exploring electrode that might be more suitable to different conditions. For instance, a specially designed spring electrode that wraps around the pipe has been developed for use with the new detector. Notwithstanding the fact that the spring makes contact at theoretically only one line of points, the sensitivity of the detector is such that complete inspection may be obtained even when moving rapidly over the section being tested. At the same time the tension of the spring assures intimate contact with the coating surface and eliminates gaps that often occur when using the metal tuft type electrode. Some types of holiday detectors are not satisfactorily adaptable for use when the coating is applied with a stationary yard type coating machine in which the pipe is rotated as it passes through the machine. Insulating covering applied in this manner can be tested by use of the Electronic Holiday Detector in conjunction with any suitable exploring electrode.

Interior Wall Inspection

The use of enamel coatings on the interior wall of steel pipes carrying water or corrosive liquids is quite common. Although the action of corrosion and tuberculation on internally coated metal pipes may not necessarily be the same as for buried metal pipes coated on the outside, any faults in the internal coating are obviously undesirable. With the new detector and a suitable electrode, a test of internal coatings may be easily and quickly made, and the location of any holiday encountered determined with reference to the end of the joint being tested.

Inasmuch as the detector can also be operated effectively even at extremely low voltage and as the instrument permits a regulation of this voltage, it is possible to inspect insulating coverings with low electrical resistance that cannot be tested with the detector that requires such a high voltage to produce a noticeable light or noise. High voltage in many instances is objectionable in that the resistance of the coating may be broken down even where holidays do not occur.

Provides Close Check of Inspection

Heretofore it has been necessary for the foreman or inspector to check very closely on the operation of the holiday detector to be certain that the operator is not missing breaks in the insulating covering due to carelessness or indifference. Tests show that even with the utmost vigilance on the part of inspectors, many voids or holidays go undiscovered and are backfilled without be-

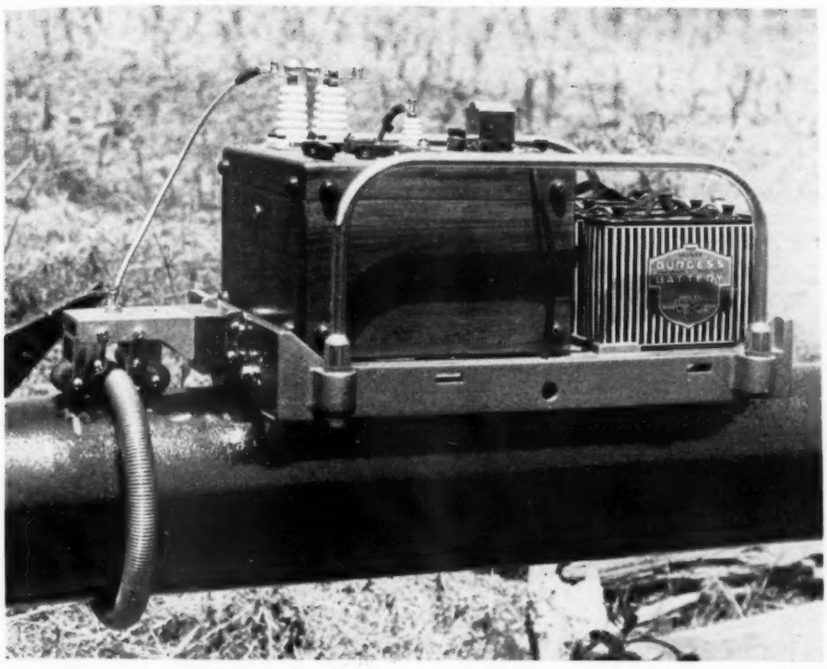

Fig. 2. Closeup of detector showing in detail the exploring electrode driving rotor. Exploring electrode spring rolls over and over as carriage is pushed along pipe line

ing repaired. When using the Electronic Holiday Detector, the foreman or inspector can hear the audible bell signal while engaged in watching the operations of the coating machine or other work going on in the immediate area and can tell in a general way whether or not a satisfactory coating job is being obtained. Furthermore, the detector registers each holiday on a counter and makes a chalk mark at the same time on the pipe near the holiday if so desired by the inspector.

Safety Features

Certain types of high voltage generators have been used for holiday inspection that are dangerous. Probably the underlying reason for using such equipment has been the endeavor to develop sufficient power either to operate some type of power-consuming indicating device directly in the inspection circuit, or to produce a spark at a holiday that would be so loud as to overcome other noises in the vicinity. Pipeliners' stories about using these high capacity generators tell of electrocuting turtles and reptiles along the right-of-way and clearly suggest the danger to workmen in case of accidental contact with high voltage. Furthermore, if an exploring electrode is allowed to remain at the location of a holiday after the initial spark has struck through, a power arc having negligible resistance immediately forms allowing a relatively large current to flow, such current being limited only by the capacity of the generator. Such a power arc generates intense heat in intimate contact with the coating material at the spot and causes it to be burned to a carbonized residue. The objection to this sort of action need not be emphasized.

A practical example of the capacity of a source of power can well be illustrated by comparing for instance the universal commercial 110-v. electrical service to a miniature dry cell battery of 110-v., of the type used in present-day portable radios. No one would expect more than perhaps an unpleasant tingle in grasping the terminals of the small battery, but who would grasp the bare wires of a 110-v. commercial lighting circuit while standing in muddy ground? Yet the miniature battery will cause just as long an initial spark as the 110 volts of the commercial circuit. In holiday inspection all that is needed is just one initial spark *if* that spark can be detected.

The Electronic Holiday Detector utilizes a high-voltage generator of comparatively low va. capacity yet high enough to maintain a few thousand volts between the exploring electrode and the pipe while supplying the current that normally flows in the high-voltage inspection circuit. The design is such that even when a holiday is intimately contacted, only a relatively small current can flow. The low va. capacity of the new detector together with other design features thus eliminate both the danger of severe shock to the operator, and the undesirable possibility of burning the coating, at the same time having actuating components with such a high degree of sensitivity that no discharge at a holiday can possibly go unnoticed.

A Step Toward Inspection Standards

The usual detector does not provide adequate means of making comparisons of the effectiveness of various types of coating and coating methods for the following reasons: (1) there is no convenient way to measure or control the voltage impressed on the coating; (2) there is a varying and undetermined leakage between the instrument and the exploring electrode through the usually lengthy high tension lead wire; (3) there is no indication as to the condition of the power supply in battery-operated units, and (4) the effectiveness of inspection is entirely dependent upon the speed of inspection and the highly variable alertness of different operators and observers.

Because the Electronic Holiday Detector eliminates all these disadvantages it offers a means for determining and setting up practical standards for the inspection of various types of coating and makes possible a comparison of their effectiveness and of the efficiency of the machines and methods applying them.

Although the discussion has for convenience been confined to the application of the new detector to the inspection of dielectric coverings on pipe lines, the apparatus is also applicable to the inspection of any facility when the degree of perfection to be obtained in a coating or sheet of insulating material is considered of such importance as to warrant a test for holidays by the high voltage method.

United First to Use New Detector

The Electronic Holiday Detector has recently been tested on miscellaneous sections of United Gas Pipe Line Company's new 8-in. line constructed to serve Camp Polk near Leesville, Louisiana. Tests were made with an inspection potential of 3000 volts and showed unusual results. In every instance where the line had been carefully checked by two 4-man crews using holiday detectors and the blemishes had been recoated, the new detector disclosed a multitude of defects in the coating, which had been overlooked. Principally such defects proved to be

pieces of carbonized coating materials, faults where sections of the coating material of one temperature had folded over coating material of another temperature, exceptionally thin spots or pits in the coating, and bare spots evidently produced by a dragging shoe of the coating head. Particularly absent were bubbles and abrasions. The coating machine used had apparently solved the matter of bubbles and as no abrasions from handling were present, it follows that all faults located resulted directly from inherent defects either in the coating machine or in the coating itself. The results of the tests indicated the following: (a) better holiday detection than that heretofore possible is imperative in order to obtain or even closely approach a perfect job of coating, and (b) a wrapper is highly desirable in the coating operation. The support of this last statement now seems obvious as many of the blemishes could not have existed had the coating at those spots been smoothed out. In other words it appears that machine wrapping the freshly coated pipe is of great importance and should be considered not as an auxiliary but as an integral part of the pipe-coating machine itself. Although the shining black surface of freshly coated pipe gives the appearance of perfection, it is unquestionable, from the results obtained by the use of the new detector, that wrapping, such as referred to, adds greatly to the efficiency of the coating application. Although the inspection voltage used was only 3,000, as compared with rumored inspection voltages as high as 35,000 on other holiday detectors, the above results were found. The sensitivity of the new detector permits the applied voltage to be reduced to such a low value that the discharge spark is microscopic and yet the warning signals and indicators are all energized in exactly the same manner as though a discharge spark of, say, ½ in. in length were produced at the holiday. In other words it is now possible to reduce applied voltages without fear of overlooking holidays because of lessened disturbance upon contact. Primarily, of course, the voltage applied between the surface of the coating and the pipe must be of sufficient intensity to cause a spark between the exploring electrode and the pipe to bridge an air gap equal to the thickness of the coating. The applied voltage must be something greater than such value in order to overcome losses, thickness of laps on wrapped line, small gaps between the contact head and the surface of the coating, the small insulating value of thin films of coating, etc. From observations made on the Camp Polk 8-in. line, it would seem that an applied effective voltage of between 2000 and 3000 would disclose all holidays of practical importance. A few sections of single coated line (no wrapper) as long as 30 ft. without holidays were found during the test, which is some evidence that the inspection voltage of 3000 is not excessive. As is well known, the time factor must be considered when making destructive insulation tests by means of high voltage. Practical tests for comparing insulations are usually divided into 3 classes; (a) rapidly applied, (b) one minute, and (c) endurance. Generally speaking any given insulation will stand a much greater voltage without breakdown for a short

Fig. 3. V. E. Hamilton, Jr., pipe-line *construction engineer of United Gas Pipe Line Company, shown with the new detector on an 8-in. company line.*

period than when subjected to a much lower voltage for a longer period of time. On the 30-ft. sections mentioned above as having been found free of holidays, arbitrary points were selected at which the potential of 3000 volts was impressed steadily for as long as 15 minutes without developing evidence of breakdown. The result points to the fact that the voltage of 3000 is definitely not destructive to a good coating during the operation of holiday detection when the exploring electrode is moved steadily along the line and constitutes a rapidly applied test.

As the impulses of the inspection voltage occur at the rate of several hundred per second no part of the coating is passed over without being subject to test even though the exploring electrode is moved rapidly over the surface of the coating. As an example of the speed obtainable with the new detector a 450-ft. section was passed over in six minutes including the time to make 12 stops to lift the pipe from skids and permit the exploring electrode to pass. Seventy-one holidays were registered on the electric counter and were marked by the automatic marker on top of the pipe. This is at the rate of about 75 ft. per min. or 1¼ ft. per second. During the passage over each 1¼ ft. or 15 in. section approximately 600 impulses were applied to the coating or one impulse to each 1/40 of an inch. Thus any one spot on the surface of the coating could not possibly be over 1/80 of an inch from any one point of the exploring electrode at the time of existence of any one wave crest of the applied voltage. As 1¼ ft. per sec. is much in excess of the extreme that might be called for in pipe-line holiday inspection work, complete coverage of every point on the surface of the pipe seems assured with the new detector. If an exploring electrode is used having some width such as say 1 in., it is obvious that high rates of speed can be reached. Although higher rates thus attainable would never be required in field work, the ability for fast operation would fit the apparatus to any inspection involving rapid motion as in checking the insulation on pipe as it comes from a stationary coating machine where pipe might be rapidly rolled past a longitudinal electrode.

A 2000-ft. section was examined with the new detector in one hour and six minutes by a 3-man crew (one operator and two observers) during which time 360 holidays were discovered and chalk marked at their specific locations. This, of course, exceeds the speed of a traveling pipe-coating machine and indicates definitely that the new detector can easily be kept within a short distance of the coating operation thus resulting in the very desirable situation of being able to disclose at once any faulty performance of the coating machine.

Equally effective on inspection where wrappers have been applied, the Electronic Holiday Detector promises to fulfill the efforts of 3 years of research, experimentation, and design to develop a practical field instrument that will contribute to the art of applying protective coatings to metallic surfaces.

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by James A. Lewis, W. L. Horner, and Marion H. Stekoll

Core Laboratories, Inc., Dallas, Texas

THE amount of recoverable oil combined with other factors, represents the return from the operator's investment. An accurate estimate of its volume enables him to space his wells more economically and to operate the area efficiently. In short, it is an important part of the answer concerning whether or not the drilling venture will be a success.

In the past this knowledge regarding recovery has remained hidden to the operator until a production decline curve has been established and extended to the economic limit. The time for establishing this decline curve generally takes several years during which time the well-spacing and general operating program will already have been developed. This development, therefore, occurs without knowledge as to what the returns on the investment might be. With the introduction of proration into the oil industry, the time required to establish a production decline curve has been prolonged. Consequently, the information regarding recoverable oil, which is necessary for efficient development of a field, has not been available to the operator from production histories until the data have lost a large part of their value.

JAMES A. LEWIS

was born August 3, 1908, in Kansas City, Missouri—Attended Southwestern College, Winfield, Kansas—Received B.S. degree from Oklahoma University in 1931; M.S. degree from Pennsylvania State College, 1932—Was an assistant professor at Pennsylvania State College, 1934-37—Has been associated with Core Laboratories, Inc., since 1937.

Within the last few years it has been found that core analysis provides a reliable aid to the problem of estimating recoverable oil. This fact has been demonstrated in many fields, the results proved, and the method established as being accurate for estimating the amount of recoverable oil obtainable from a formation. The use of core analysis to estimate recoverable oil is becoming more important for two reasons; first, the data have been found to be accurate, and second, the results are available shortly after the cores are brought to the surface and long before the field has been developed.

The applicability of core analysis data in estimating recoverable oil depends on several factors. One is that complete analysis of the cores must be made. Partial or incomplete analysis, coring and testing of intermittent sections of the formation are not conducive to accurate and reliable results. In addition, cores require careful analysis immediately upon being brought to the surface. Transportation of cores, even in sealed containers, has been found to cause erroneous results with regard to the fluid content of the core. Sweating of the core against the sides of the container apparently occurs during transportation and results in measurements that are not directly comparable with those obtained at the well site. Once the core analysis has been made, proper understanding, use, and interpretation of the data are necessary to translate the core analysis results to accurate and reliable estimations of recoverable oil.

Applicability

Before explaining how results of core analyses are used to estimate recovery, it is desirable to present several illustrations indicating the applicability of core analysis results to actual field data. In Fig. 1 is shown the actual and estimated recovery in bbl. per acre-ft. for five acres. Because of the confidential nature of the work with regard to the calculation of the recovery of these fields, their names are omitted. These five acres are representative, however, of the accuracy that may be expected from core analyses with regard to the estimation of recoverable oil from a particular formation. It may be noted that the estimated recovery is neither consistently high nor consistently low as compared with the recovery obtained; in each instance, the estimated figure is reasonably close to the actual.

The rapidity with which recoverable oil may be calculated from core an-

W. L. HORNER

received a degree in petroleum geology from University of Pittsburgh in 1928 and later a degree in petroleum engineering from the same institution—After geological field work in South America, received training as student engineer, Standard Oil Company, New Jersey, and from April, 1929, to October, 1932, was in charge of a production research department laboratory for Humble Oil and Refining Company, Houston, Texas—From October, 1932, to January 1, 1936, was employed by Forest Oil Companies as research engineer—Since January 1, 1936, has been connected with Core Laboratories, Inc.

MARION H. STEKOLL

received bachelor's degree from Stanford University, California, in 1937—Later received degree of petroleum enginer in the graduate school of engineering, same university—Since July, 1939, has been employed by Core Laboratories, Inc., as a petroleum engineer.

alysis and the information made available to the operator are factors that add to the value of the data. After a well has been cored and the cores analyzed at the well site, the information with regard to recoverable oil may be available to the operator within two or three days. These data are often obtainable before the well is completed or perforated, and may be of significant value to the operator with regard to selective perforation or completion of the well. Through knowledge of core analysis, different areas in the field may be correctly evaluated and the proper well-spacing and development program carried out from the beginning of operations.

Under the primary recovery operations, there are two general types of recovery to be considered in estimating recoverable oil; the first is water drive and the second, gas-expansion production.

Water Drive

An estimation of recovery by water drive (original bottom-hole pressure maintained) may be made directly from complete core analysis measurements and calculations. Knowing the residual oil saturation in the cores, the shrinkage or formation volume factor as estimated or obtained from bottom-hole sample analysis, the connate water and porosity from the core analysis, it is possible to calculate recovery by water drive with an accuracy such as illustrated in fields No. 4 and 5 in Table 1.

When the variables listed above are known, it is convenient to use a chart such as shown in Table 2 to calculate the recovery by water drive. The various factors necessary for the use of this chart—porosity, connate water, and residual oil saturation—are obtainable from core analysis. Formation volume factor may be estimated or accurately determined from bottom-hole sample analysis.

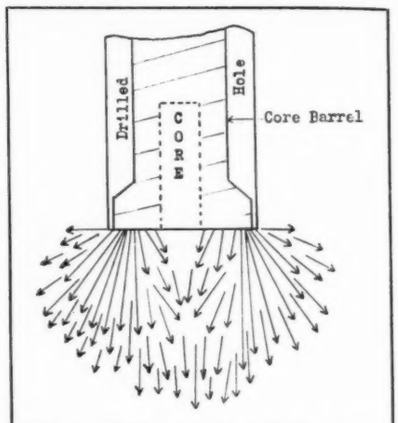

Fig. 1. Flushing action during coring by water from drilling mud—advancing front of water from mud flushes formation ahead of core barrel

A discussion of residual oil saturation as found in cores and the determination of connate water is probably applicable at this point.

When wells are cored, the mud pressure at the bottom of the hole is greater than the formation pressure, hence infiltration of water from the mud occurs ahead of the coring bit. A diagrammatic illustration of the way this water penetration may take place is shown in Fig. 1. Consequently, when

Fig. 2. Comparison of residual oil saturation found in cores, with and without mud in hole during coring

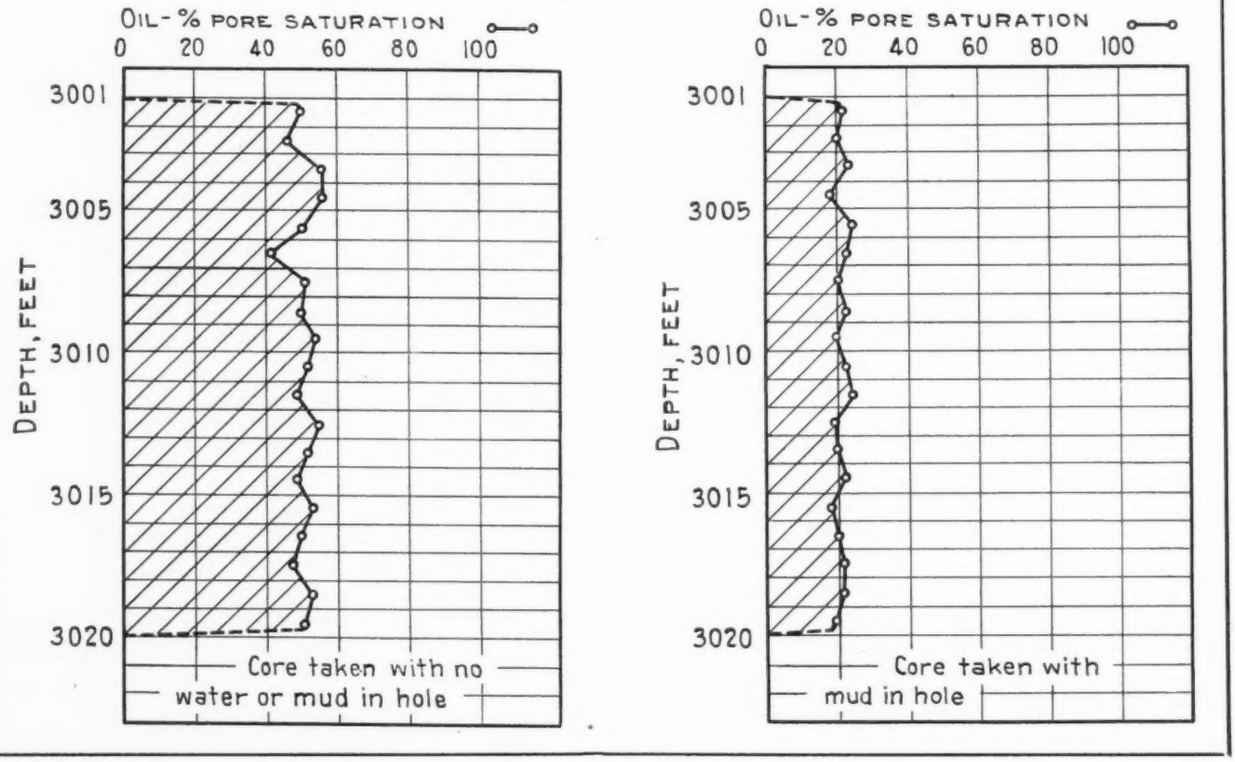

TABLE I

Field no.	Actual oil recovery**, bbl. per acre-ft.	Estimated oil recovery, bbl. per acre-ft.	Type of production
1	200	178	Gas-expansion
2	205	231	Gas-expansion
3	270	258	Gas-expansion
4	590*	679	Water drive
5	970*	1003	Water drive

Fig. 1: Actual vs. estimated oil recovery (by core analysis).

*A small amount of production is yet obtainable.

**Actual oil recovery or recovery estimated by projecting well-established production decline curve.

the core is cut, it is flushed by water under reservoir conditions, and the residual oil saturation in the core, corrected for shrinkage, is indicative of the residual oil after water-flooding or water drive. Flushing action by water from drilling fluid may be illustrated by cores taken from the same formation, one core taken with mud in the hole, and the other cut "dry," no water or mud in the hole. Such cores show a difference in residual oil saturation as illustrated in Fig. 2. It may be observed that the core taken with mud in the hole has a much lower residual oil saturation than the core taken "dry." The actual saturations obtainable in various fields will vary according to sand and reservoir characteristics. The residual saturations in the examples are, therefore, illustrative of only a specific formation. In numerous fields, the residual oil saturation in the cores at the surface is commonly found to vary between 8 and 25 percent of pore space.

Inasmuch as cores from rotary wells are usually flushed by water from the drilling mud, the residual oil saturation in the cores, corrected to bottom-hole conditions, is indicative of the amount of oil that will be *left in* the formation after water drive. This residual oil value must be subtracted from the total pore space in the formation for the calculation of recoverable oil under water-drive conditions.

Another value to be subtracted from the total pore space is the connate or interstitial water present in the producing horizon. As cores are contaminated during the coring operation by water from the drilling fluid, it is obvious that the total water saturation as found in cores represents both connate and drilling fluid water. As a result of research and the use of accurate data, it has been found possible to correlate calculated connate water saturation as obtained from core analysis with actual connate water values. The derived correlations have been obtained (by coring with oil-base mud, by dry coring, and by tracers) in a large number of formations and the maximum deviation that has been found to date is about 3 percent of pore space. The calculated connate water saturation in oil-producing horizons has been found to vary between 13 and 45 percent of pore space, with a few extremes on both sides of this variation.

The importance of knowing connate water is shown by taking two values from Table 2. Using a porosity of 25 percent, a residual oil saturation of 15 percent, and a formation volume factor of 1.25, the recovery for 20 percent connate water is calculated to be 951 bbl. per acre-ft. If the connate water were 40 percent of pore space, all other factors remaining the same, the recovery would be 640 bbl. per acre-ft. The effect of this generally "unseeable" variation in connate water is of marked importance in setting up the true values for the field. If, for instance, and simplifying the problem, the formation were 10 ft. thick, the recovery per acre when connate water equals 20 percent would be 9510 bbl.; for 40 percent the recovery per acre would be 6400 bbl. Considering 20-acre spacing, as an illustration, a recovery of 190,200 bbl. per well would be obtained for 20 percent connate water, and 128,000 bbl. would be ob-

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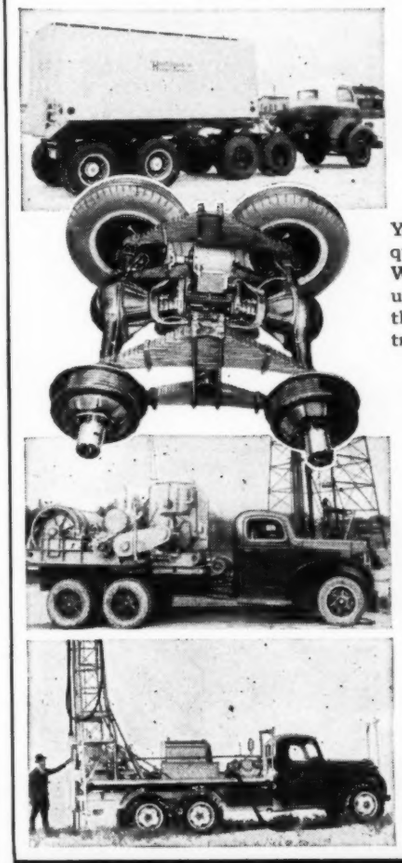

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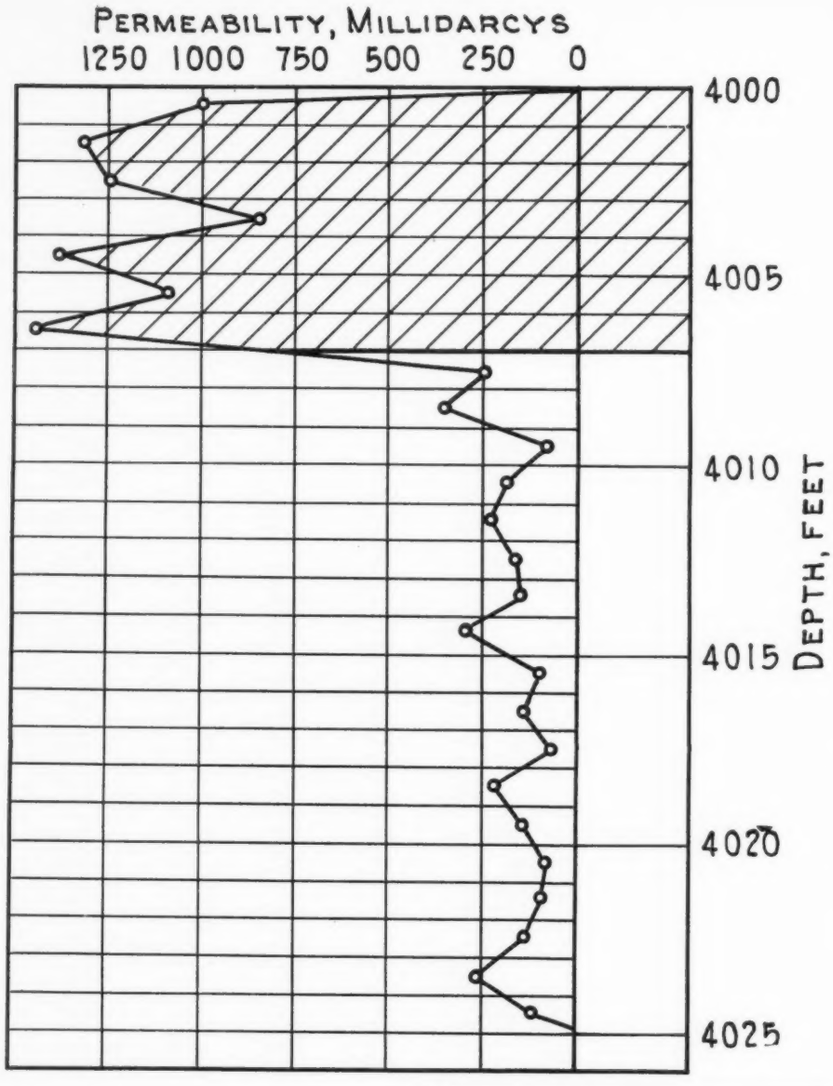

Fig. 3. Illustrating water-flooding of higher permeability zone

applicable to water drive in Fig. 3 would be limited to the section of higher permeability or about 7 ft. The entire formation thickness of 25 ft. would not be floodable under water drive, therefore, unless the highly permeable section at the top was shut-off after being depleted. In some instances, when the exact position of a highly permeable zone is known, it has been possible to shut-off encroaching water and to produce clear oil from sections of lower permeability. The application of recovery calculations by water drive must, therefore, take into consideration the variation of permeability profile in the well in question.

In fields in which the viscosity of the oil is high in comparison to water, the variation of permeability is in effect magnified and the reduction of permeable, floodable thickness may result.

If the permeability and other variations are such as to permit complete water-flooding of a particular horizon, the efficiency of recovery by water drive may be quite high. When connate water is 30 percent of pore space, the total amount of oil and gas in the formation equals 70 percent of the pore volume. When the residual oil as found in the formation after flooding is 18 percent of pore space, the recovery equals 74.3 percent of the total oil and gas available. The efficiency of water drive under such conditions may be considered as satisfactorily high.

tained with 40 percent connate water. The difference of 62,200 bbl. per well is, of course, of great significance in indicating economical field operations.

In using the recovery calculated by water drive, it is necessary to take into consideration such factors as viscosity of oil, well-spacing, permeability, etc. An example of the effect of permeability on estimating the recovery by water drive is illustrated in Fig. 3. In this figure the measurement of permeability for each foot of formation is shown. Under water-drive conditions the water would encroach through the highly permeable portion of this formation first. This is shown in Fig. 3 as the shaded area between the depths of 4000-07 ft. When this highly permeable zone has been flooded out, water will be produced by the well—in the above instance, as a large percentage compared to the oil produced from the lower permeability section below. If this percentage of water is sufficiently high to cause abandonment of the well, the formation thickness

TABLE 2

The recovery of oil by water drive

(Original bottom-hole pressure maintained)

Oil recovery by water drive—bbl./acre-ft.

Knowing porosity, residual oil saturation in the cores, and formation volume factor, the oil recovery by water drive for different connate water values may be approximately determined from this chart.

CONNATE WATER—% PORE SPACE

		20			25			30			35			40		
		FV			FV			FV			FV			FV		
○	So	1.15	1.25	1.35	1.15	1.25	1.35	1.15	1.25	1.35	1.15	1.25	1.35	1.15	1.25	1.35
15	10	693	629	573	643	582	530	592	535	487	542	489	444	491	442	401
	15	635	570	515	585	524	472	534	477	429	483	431	386	433	384	343
	20	577	512	457	526	466	414	476	419	371	425	372	328	375	326	285
20	10	924	838	764	857	776	707	789	714	650	722	652	592	655	590	535
	15	847	761	687	779	698	629	712	636	572	644	574	514	577	512	457
	20	769	683	609	702	621	552	634	559	494	567	497	437	499	434	379
25	10	1156	1048	956	1071	970	884	987	892	812	903	815	740	818	737	668
	15	1059	951	859	974	873	787	890	795	715	806	718	643	721	640	571
	20	962	854	762	877	776	690	793	698	618	709	621	546	624	543	474
30	10	1387	1257	1146	1285	1164	1061	1184	1071	974	1083	978	888	982	885	802
	15	1270	1141	1030	1169	1048	944	1068	954	858	967	861	772	865	768	685
	20	1154	1024	914	1053	931	828	951	838	742	850	745	655	749	652	569
35	10	1618	1467	1338	1500	1358	1237	1382	1249	1137	1264	1141	1036	1145	1032	936
	15	1482	1331	1202	1364	1222	1101	1246	1114	1001	1128	1005	900	1010	896	800
	20	1346	1195	1066	1228	1086	966	1110	978	865	992	869	765	874	760	664

So = Residual oil saturation in cores.
FV = Formation volume factor.
○ = Porosity.

Gas Drive

The calculation of recovery by gas-expansion production is based upon data similar to those for water drive, with the major difference that the residual oil left in the formation under gas-expansion is almost invariably higher than that left in the formation after water drive. Correlation between core analysis measurements and the recovery obtainable in a gas-expansion field have resulted in accurate relationships being developed. Examples of the accuracy with which recovery by gas-expansion may be calculated is illustrated by fields No. 1, 2, and 3 in Table 1. The utilization of core analysis correlation, economic limit of production, and the reservoir pressure at the time of abandonment enable accurate estimates to be made with regard to the recovery obtainable in gas-expansion type fields.

By using production records to estimate the total recovery, a correct figure may be obtained; but, generally speaking, the time of obtaining this figure will be several years after the beginning of field development. Under proration the length of time required to determine the recovery obtainable is considerably lengthened. With complete records regarding the reservoir, not only is the recovery accurately estimated in advance, but an even more significant point is achieved. That is, the "maximum" possible recovery from the reservoir is known at the beginning of the field development. With this information, the drilling of the field does not take place in a haphazard manner, but is carried out to obtain as nearly as possible the maximum economical recovery that the reservoir is capable of yielding. With such information the proper and economical well-spacing, reservoir pressure control, and general field operation may be carried out with the best results. The financial, drilling, and producing program, when complete reservoir knowledge is available, may be worked out in advance. Inasmuch as the controlling engineering features of a field, as a result of recent developments in core analysis and reservoir engineering, are now largely subject to complete measurement and understanding, efficient operation and control of the reservoir is possible.

It may be emphasized that thorough knowledge of the reservoir is of utmost importance with respect to economical field operation. Today, emphasis is being placed on reservoir data and control rather than on well operation. Although the control of a well is important, the well is but the conductor that brings the fluid to the surface. The reservoir characteristics determine the type and amount of fluid available, proper well-spacing, and production. A thorough understanding of the reservoir itself is of prime importance to an efficient oil operator.

Once the field has been developed and the recovery by primary production obtained, complete information obtained from cores as applied to recoverable oil will indicate possibilities for secondary recovery operation. Secondary recovery operations under such circumstances may be carried out with a surety and an exactness of performance that will enable calculation of return on investment before the investment has been made. For instance, in a gas-expansion field, the total recovery possible by artificial water drive or by gas repressuring compared with that already obtained from the field will indicate the amount of recovery obtainable by either type of secondary recovery procedure. In water-drive fields the knowledge of the permeability profile, the recovery obtained, and the optimum yield will enable computations to be made with regard to the area drained by the water drive. Determination may then be made with regard to the feasibility of workovers.

With core analysis and reservoir characteristics understood, the operator works with a picture of the returns on his investment and the best way of obtaining these returns laid out before him.

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☆ Review of recent developments on many fronts stresses importance of continual support by industry of research work

by Lester C. Uren

Professor of Petroleum Engineering, University of California

THE efforts of research workers in laboratories and engineers in the field continue to enrich our knowledge and understanding of the problems that surround the petroleum producing industry. Research and development staffs of the more progressive oil companies, equipment manufacturers and service organizations, and technologists employed in government bureaus, other public and semi-public agencies, universities, and colleges, each year make notable contributions to the advancement of petroleum production technology. Professional societies, industrial institutes, and technical and industrial journals publish the results of this research so that all may share in the added efficiency that is made possible by their application to industry. The year immediately preceding this annual engineering issue of *The Petroleum Engineer* has been one of particular achievement in the field of petroleum production research despite adverse influences that might have been expected to result in curtailed appropriations and diminished interest.

It is difficult in the brief space here available to do more than mention the many different research contributions to our knowledge of petroleum production technology that have appeared in the technical press during the last year. No detailed appraisal of the results is here possible, and the writer's only purpose in preparing this article is to provide a guide that might lead the reader to the primary sources of information in which he may be interested. No pretense is made to completeness and doubtless important contributions that have escaped the writer's attention have been omitted in the following sketch. One would indeed be presumptous to seek to evaluate all the thought and effort that goes into a whole year of research by so ambitious a group as our petroleum production technologists, within the space afforded by a brief article. In later articles, devoted to more specific phases of the field of petroleum engineering research, an effort will be made to appraise in greater detail the progress that has been made, and to visualize some of the future trends.

L. C. UREN

is professor of petroleum engineering at the University of California—He received his Bachelor of Science degree from the College of Mining, University of California, in 1911 and has taught courses in mining and petroleum engineering there since 1912, ranking as senior professor in the petroleum division of the department of mining since the inception of the division in 1915—He has supervised the preparation of more than 100 senior and graduate theses in petroleum technology and is a member of the research committee and director of Project No. 28 of the American Petroleum Institute, and a member of the research committees of the American Association of Petroleum Geologists, of the American Institute of Mining and Metallurgical Engineers, and of the National Research Council—His teaching duties have restricted his commercial work to consultation and appraisal on behalf of several important companies and federal and local governmental agencies and as an expert witness in litigation—He is a member of the professional societies mentioned, and of Sigma Xi, Tau Beta Pi, and Theta Tau honorary fraternities—He is author of more than 100 papers on petroleum technology and of two volumes on petroleum engineering extensively used as text and reference books.

Fundamental Properties of Hydrocarbons

The research worker is particularly gratified in the accumulation of knowledge in what is called "fundamental research": research that underlies and relates to the entire field of petroleum technology. The industry does not support enough of this type of research. Usually it seems to have no particular application and does not lead to patents. Oil company executives have difficulty in justifying it as a short-term investment; yet, in the long view, it is probably of greater value than the projects of immediate or very specialized interest. Individual oil companies may not be able to afford expenditure of much of their research funds in the pursuit of fundamental knowledge, but collectively they may do so with profit. Indeed, it is an obligation that every important industry should support efforts looking toward the amassing of such fundamental data as that industry needs.

In recognition of this principle, the American Petroleum Institute has for many years been supporting a program of fundamental research on projects of general interest to the petroleum industry. When this effort was first sponsored by the Institute, a very ambitious program comprising more than forty projects was undertaken and funds aggregating half a million dollars were subscribed to endow this program over a period of years.

Since these funds were exhausted, the program has been kept alive on a much smaller scale by annual contributions from a few of the larger oil companies. Three especially worthy projects of fundamental character have been carried forward through the years and are still continuing.

One of these, however, a study of the "Origin and Environment of Source Sediments", is now in its final stages and a monumental treatise presenting the results of many years of intense research is now being prepared by Dr. P. D. Trask of the U. S. Geological Survey, who has directed the project since its inception.

The A.P.I. project that has probably commanded the greatest interest among technologists active in the petroleum industry is the one devoted to a study

of "The Fundamentals of Hydrocarbon Behavior", directed by Professor W. N. Lacey. Lacey, Sage, and their several co-workers at the California Institute of Technology have, through recent years, assembled a vast amount of fundamental data on phase equilibria in hydrocarbon systems and related subjects in the fields of physical chemistry and thermodynamics. This has involved development of new types of apparatus[1] for making volumetric measurements and determining the physical properties of hydrocarbon liquids and gases at high temperatures and pressures. Nearly seventy papers and a book have resulted from this invaluable research and the data assembled are of inestimable value to technologists engaged in all phases of the petroleum industry. During the last year, nine papers have been published and others are in preparation. Most of these have been printed in *Industrial and Engineering Chemistry* as part of a series under the general title, "Phase Equilibria in Hydrocarbon Systems", but some have been published by the American Institute of Mining and Metallurgical Engineers.[2, 3, 4]

Other investigators have also been active in studying the fundamental properties of hydrocarbons as they exist under reservoir conditions. Technologists of the U. S. Bureau of Mines[5] have described a type of cell for studying the PVT relationships of hydrocarbon mixtures under high temperatures and pressures and H. T. Kennedy[6] of the Gulf Research and Development Company has published a useful paper indicating the value of such data in studying reservoir conditions and in planning field development operations. Professor D. L. Katz[7] and his associates in the University of Michigan have published a valuable paper on the phase relationships of the components of natural gas and natural gasoline under high pressures and temperatures. Our knowledge of the compressibility of natural gas under high pressures and the extent of variation from Boyle's Law has been extended by Professor G. G. Brown and associates,[8] also of the University of Michigan, and by R. L. Cochran[9] of the Texas Railroad Commission staff. J. E. Sherborne[10] of the Union Oil Company of California has concisely presented the fundamentals of hydrocarbon phase relationships in a paper published by the American Institute of Mining and Metallurgical Engineers.

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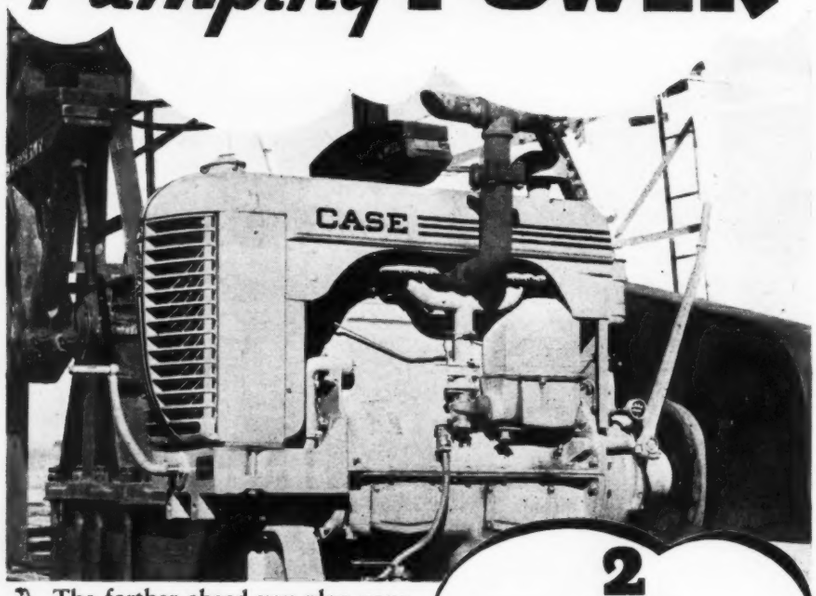

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Reservoir Conditions and Performance

Interest continues in the further study of conditions existing within deep-seated oil reservoir rocks and of the natural forces that govern expulsion of oil and gas from reservoir rocks. For many years, this field has been a prolific source of research data, and much of the newer technique practiced by the petroleum production engineer has been based on concepts of oil drainage thus gained. Present-day methods of oil production bring to the surface but a fraction of the oil originally present in the oil fields. Better understanding of conditions existing within the reservoir rock and of the forces influencing drainage, should lead to development of more efficient methods of oil recovery. With the hope of improving production efficiency, many of the larger oil companies have been willing to support research having this objective, and public and semi-public research agencies, sensing the economic importance of this objective, have also been active.

A recent meeting of the American Petroleum Institute featured a symposium on "reservoir performance", with papers prepared by three of the more prominent authorities[11, 12, 13] on this subject, seeking to define the problems presented and to interpret what has thus far been learned by previous years of research on drainage fundamentals. One of the fundamental research proj-

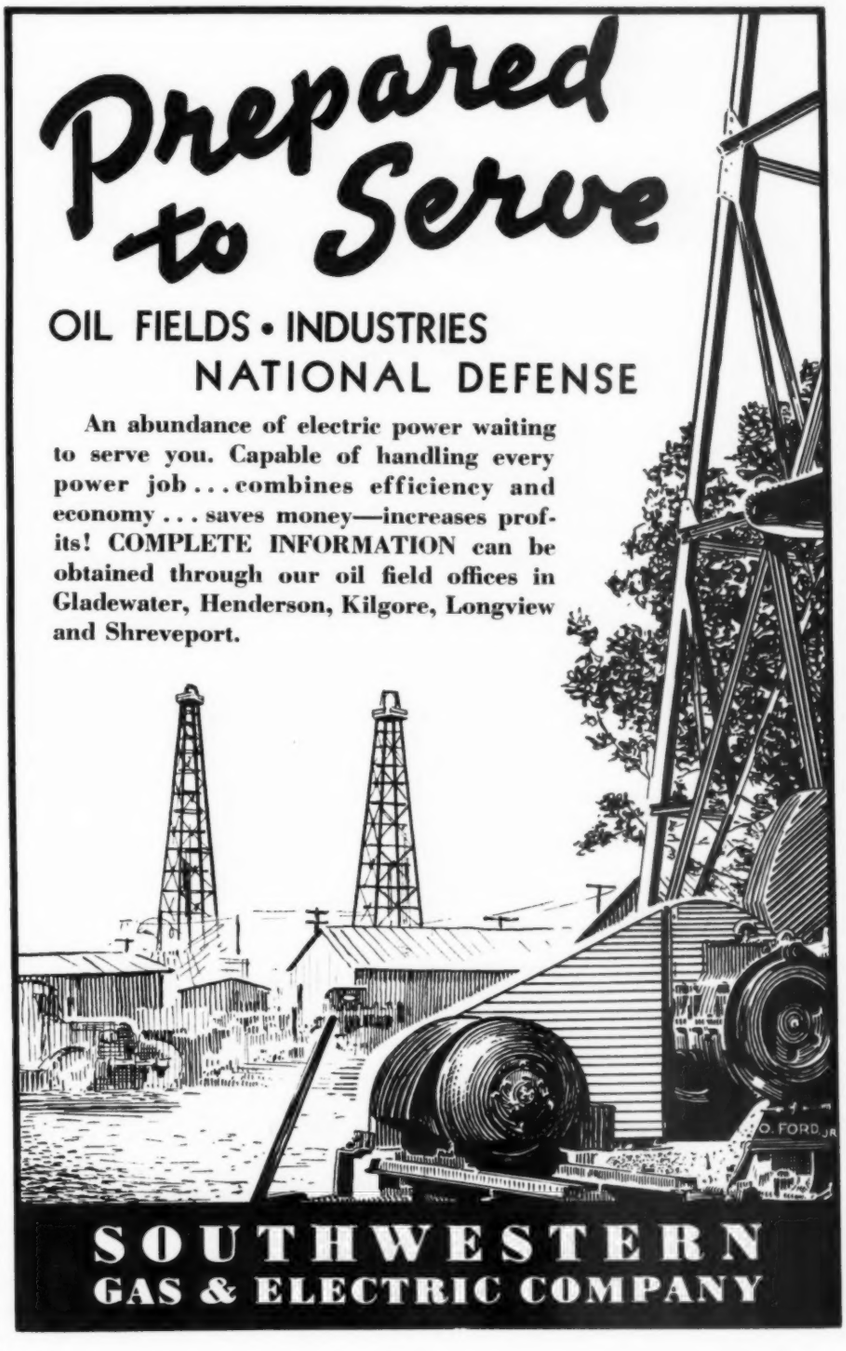
ects supported by the American Petroleum Institute, previously mentioned, is entitled, "Function of Water in the Production of Oil from Reservoirs." Conducted under the direction of Professor F. E. Bartell of the University of Michigan, this project has been concerned with the mechanics of displacement of oil from reservoir rocks by water under pressure, and with the adsorption, adhesion, and interfacial tension phenomena that control release of the oil. During the last year, a paper dealing with the influence of adsorbed films on the wetting characteristics of mineral surfaces, has been published by Bartell[14] and his associate, K. E. Bristol. Other papers resulting from this research are in preparation.

C. B. Carpenter and G. B. Spencer[15] of the U. S. Bureau of Mines staff have investigated the compressibility of consolidated oil-bearing sandstones and conclude that they are not sufficiently compressible to influence seriously computations of reserves or reservoir performance in production. The mechanism by which fluids are displaced from sands and the factors influencing displacement efficiency have been studied and reported upon by S. E. Buckley and M. C. Leverett[16] of the Humble Oil and Refining Company. Leverett and W. B. Lewis[17] of the same organization have investigated the mechanism involved in steady flow of two- and three-phase systems of gas, oil, and water through unconsolidated sands. H. G. Botset[18] of the Gulf Research and Development Company has also contributed a valuable paper on the flow of gas-liquid mixtures through consolidated sand.

During recent years, much progress has been made in the development of instruments and technique for determining reservoir pressure and temperature in producing wells. E. W. McAllister[19] of the Western Gulf Oil Company has published an interesting and valuable assemblage of data showing how subsurface pressure data are assisting in solving the development and production problems of one of California's major oil fields. Methods of measuring deep-well temperatures and of utilizing temperature data in the solution of a variety of practical field problems, have been reviewed in a timely paper by C. V. Millikan[20] of the Amerada Petroleum Corporation. U. S. Bureau of Mines technologists[21] have also contributed an interesting report showing how well temperature data may aid in the study of subsurface leakage of gas from one formation to another.

Testing Crude Petroleum and Formation Samples

An important aspect of petroleum production technology is that concerned with the analysis of oils to determine their properties and the testing of formation samples taken in the course of drilling, to determine their porosity, permeability, and fluid content. For many years, technologists of the U. S. Bureau of Mines have been engaged in sampling and analyzing crude petroleums from all the important oil-producing fields of the United States and the results have been made available from time to time in reports issued by the Bureau. Three new publications in this series have appeared during the last year, giving the results of tests on oils from fields of Texas,[22] Arkansas,[23] and Illinois.[24] H. M. Smith of the Bureau staff has also prepared a publication in explanation of a newly devised "correlation index" for classifying crude petroleums on the basis of results of Hempel distillation tests.[25] Another publication by Bureau of Mines technologists describes the apparatus used and method employed in determining the water content of oil sands,[26] while still another discusses the methods used in extracting and quantitatively determining the water-soluble chloride salts in petroleum.[27] K. B. Barnes of the Gulf Oil Corporation de-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scribes an improved type of retort for making saturation tests of formation samples.[28] H. Hoover, Jr., and H. Washburn[29] of the United Geophysical Company have briefly discussed a new method of quantitatively determining the various hydrocarbons in soil or formation samples, involving use of the mass spectrometer.

Methods of making and interpreting the results of tests made on core samples from drilling wells continue to interest petroleum production technologists. During the last year, Professor A. J. Carlson and M. C. Eastman of the University of California have studied and competently discussed the different test factors that enter into a determination of the permeability of formation samples.[30] K. B. Barnes of the Gulf Oil Corporation describes an improved method of mounting core samples in apparatus used for determining permeability.[31] Some technologists have questioned whether permeability tests, in which a gas is used as the test medium, correctly determine the permeability of the sample to oil. L. J. Klinkenberg[32] of the Shell Development Company has investigated this experimentally, and in a recent American Petroleum Institute paper presents the results of his studies. It is generally supposed that the average permeability of a series of core samples taken through a productive interval, should give a fair basis for predicting the productivity of a well penetrating this interval. J. E. Sherborne[33] of the Union Oil Company of California shows that there are wide discrepancies in results when such procedure is followed. Sherborne has also compared results on porosity and permeability and saturation tests by different commercial laboratories and finds fair agreement on porosity determinations but wide discrepancies in results of fluid content tests and only fair agreement on permeability tests.[34]

Service organizations have lately been developing coring devices for securing samples from the walls of wells previously drilled. H. L. Flood of the editorial staff of *The Petroleum Engineer* discusses this technique as it has been developed and applied in the Gulf Coast region.[35] Recently the Well Spacing Committee of the American Petroleum Institute has sponsored development of a device for taking cores under conditions that permit of removing them to the surface without loss of pressure or contained fluids. The U. S. Bureau of Mines and technologists of the Carter Oil Company have collaborated in this work. A paper by J. J. Mullane of the Carter Oil Company gives results of tests made on cores taken with the Carter pressure core barrel, and finds that more complete and dependable core data are to be had through use of this device.[36] N. Johnston of the General Petroleum Corporation presented at a recent American Petroleum Institute meeting a critical analysis of the entire procedure of core testing and analysis and a review of the applications of such data in oil-field exploitation.[37]

Electrical Logging and Well Surveying

Though first introduced as a well-logging technique only ten years ago, the resistivity method of well surveying has attained wide use and a large percentage of the wells currently being drilled in California, Gulf Coast, and Mid-Continent fields are logged by this method. There is yet much to be learned in the scientific application of electrical logging and interpretation of the results, and research is gradually closing the gaps in our knowledge of this art. J. Zaba of the Rio Bravo Oil Company offers an interesting discussion of the limitations in current electrical logging practice.[38] As yet, electrical logs possess only qualitative significance and efforts are being made, through correlation with core samples taken by mechanical means, to interpret the results quantitatively. P. B.

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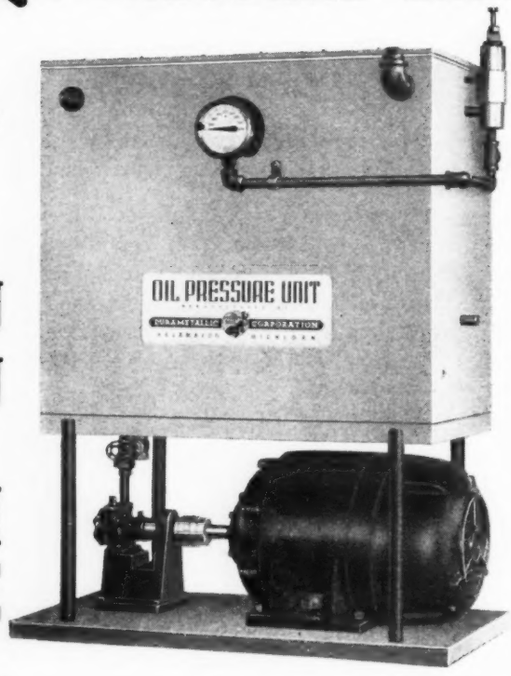

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Leavenworth[39] of the Gulf Oil Corporation has prepared a paper presenting the results of comparisons between electrical logs and analytical data obtained by core testing. Until recently, electrical logs were prepared as a separate operation, by running a system of electrodes through the well while the drill pipe is out of the hole, thus occasioning some delay in drilling. Now, through a new development, a resistivity log may be obtained continuously while the drill is at work. J. T. Hayward[40] of the Barnsdall Research Corporation refers to this new procedure in a recent paper. The electrical circuit and equipment employed were fully described in a previous article.[41]

Because of its simplicity and low cost, many operators still make use of hydrofluoric acid bottles as a means of measuring the amount of deflection of wells from the vertical. This method of well surveying is a rather primitive one and several factors inherent in the method operate to impair is accuracy, as is shown in a paper by G. H. Scott.[42]

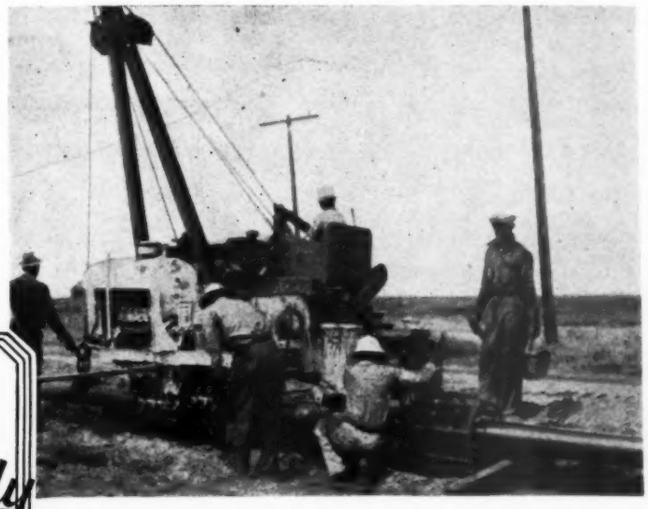
Well Spacing

Though a committee of the American Petroleum Institute has for many years been engaged in a critical study of the factors governing the economic spacing of wells in oil-field development, the subject is one of great complexity, and no scientifically complete solution of the well-spacing problem can yet be said to have been found. Much progress has been made, however, as is shown by a recent review of the principles thus far established, by M. Muskat of the Gulf Research and Development Company.[43] The results of a field study of different well spacings in one of the Mid-Continent fields has been prepared by M. G. Cheney[44] of the Anzac Oil Corporation.

Drilling Fluids

Scientific study of the functions and properties of drilling fluids began more than twenty years ago, and "mud-fluid" research has been active ever since. One would think that by now we might have learned all there is to know about drilling fluids, but interest in this subject has of late been more intense than ever before. Through publications giving the results of many research projects in this field, the last year has been one of notable progress. In such a field as this, concerning which several hundred technical papers have been published, it is helpful to assemble a digest of what has previously been learned, for the guidance of those who do not have time or library facilities to do this for themselves. Such a contribution, reviewing progress in the technology of drilling fluids, has lately been prepared by A. G. Stern[45] and made available by the U. S. Bureau of Mines. The Bureau has also published a new edition of an earlier publication[46] on the properties, preparation, and utilization of bentonite that will be of interest to petroleum technologists concerned with the preparation of drilling fluids. Bureau of Mines technologists have also contributed three useful papers dealing with different types of tests and testing devices useful in making technical studies of the physical and chemical characteristics of water suspensions of clay. A. G. Stern[47] has described a device that he calls the "Eykometer" for measuring the yield point or solidifying strength of gelled clay fluids. G. L. Gates[48] has reviewed the methods for determining particle-size distribution and colloid content of drilling fluids, and a report by G. T. Faust[49] describes a new staining technique for the detection of bentonite and other clay minerals.

Notable among the year's contributions to our knowledge of the fundamental colloidal properties of water-suspensions of clay, is one by A. G. Loomis, T. F. Ford, and J. F. Fidiam[50] of the Shell Development Company. New data are presented bearing upon the influence of chemical treatment on



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the viscosity and thixotropic properties of drilling fluids. Results of a thoroughgoing Ph.D. thesis conducted at the University of London, involving a study of the same topics, with particular emphasis upon methods of measuring such fundamental properties as viscosity, shear, and yield values, and presenting an excellent bibliography, have been contributed by G. D. Hobson.[51] H. T. Byck,[52] also of the Shell Development Company, offers a paper presenting new data indicating that the plastering behavior of mud fluids is dependent primarily upon the properties of the fluid and is independent of the formation permeability.

Field studies of the problems of drilling fluid control have been productive of several interesting publications during the last year. H. C. Darley[53] writes of methods employed in the oil fields of Trinidad for determining and controlling properties of mud fluids at the well. M. L. Cashion[54] of the Gulf Oil Corporation describes pressure drilling equipment and methods of chemical treatment of mud fluid to prevent flocculation normally resulting from contamination with salt water in deep-drilling operations in the Gulf Coast region. R. J. S. Pigott[55] of the Gulf Research and Development Company, discusses the flow characteristics and friction losses incurred in pumping drilling fluids through the circulating system of rotary-drilled wells. H. W. Hindry[56] of the Shell Oil Company, discusses the preparation and properties of oil-base drilling fluids useful in drilling through oil-producing formations under certain conditions.

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Oil-Well Cements

Successful exclusion of water from wells requires accurate knowledge of conditions within the well and close control of the composition of the cement used and of the methods of preparation and placement of the cement slurry. During the last twenty years, research has contributed much to our understanding of the behavior of cement under deep-well conditions and to the development of cements especially adapted to such conditions. Four contributions to our knowledge of cement technology that have appeared during the last year seem particularly worthy of mention. R. F. Farris[57] of the Stanolind Oil and Gas Company presents results of studies of the effects of high temperature and pressure on the setting properties of cement slurries and finds that both tend to hasten the setting time, until at pressures as great as 5000 lb. and temperatures above 180°F., the slurry stiffens too rapidly to permit proper placement in a deep well. Need for development of new types of cement that can be successfully used under such conditions is indicated. P. H. Jones and D. Berdine[58] of the Union Oil Company of California, discuss the conditions that influence the quality of the bond between the cement and the formation exposed in the wall of the well. W. A. Sawdon[59] of the editorial staff of *The Petroleum Engineer*, gives results of the experimental use of a special type of cement that is soluble in acid, the cement being locally dissolved after setting and hardening in the well, by applying acid through gun-perforations in the well casing. Common practice has hitherto been to use only neat cement in water exclusion operations in oil wells, but Sawdon[60] discusses a new practice in which sand is added to the cement slurry.

Gravel-Packing

Use of gravel or coarse sand as a screening medium about liner perforations to restrict incursion of fine sand from the reservoir rock, though a comparatively recent development in oil-field practice, has been the subject of several research projects, results of which have lately been published. B.

Gumpertz[61] and K. E. Hill[62] present the result of theses conducted at the University of California, designed to determine the effects of gravel grain-size, thickness of pack, rate of fluid flow, pressure conditions, and other factors that influence the efficiency of gravel as a screening medium. Hill also presents results of applications of gravel-packing in the Wilmington field of California. Professor W. N. Lacey and B. H. Sage[63] of the California Institute of Technology present some of the results of several years of research on different aspects of gravel-packing, supported by the Texaco Development Corporation. Their efforts were directed particularly toward studies of the effects of gravel size and condition of packing, sand size distribution, fluid velocity and viscosity, and thickness of gravel screens on screening efficiency. Their research also confirmed previous concepts of the advantages of sustained large well diameters, possible by use of gravel in well cavities, in increasing the rate and efficiency of oil production.

Several papers present the results of field applications of gravel-packing. W. A. Clark[64] of The Texas Company stresses the economic advantages resulting from use of the method in certain California fields, and M. L. Cashion and F. B. Markle[65] of the Gulf Oil Corporation review the results of many successful applications in the Gulf Coast fields. H. L. Flood[66] of the editorial staff of *The Petroleum Engineer* discusses the advantages of gravel-packing as a means of facilitating injection of gas into producing formations in cycling projects.

An important contribution to our knowledge of the fluid forces operative about a slotted liner in a high-pressure flowing well, is found in a paper by F. G. Miller[67] of the U. S. Bureau of Mines. This paper is an outgrowth of research conducted in candidacy for the M. S. degree at the University of California.

Chemical Well-Completion and Cleaning Methods

Chemistry is playing an increasingly important role in oil-field exploitation, particularly in the completion and conditioning of wells to stimulate production and control incursion of water. The many applications of chemical methods in these and other field problems are reviewed by W. W. Robinson[68] of The Texas Company. S. C. Morian[69] of Dowell Incorporated, discusses the use of acids in wells as a means of cleaning the walls of the well of adherent clay deposited by the drilling fluid. Oil sands exposed in the walls of a well may be made water-repellent by treatment with certain reagents that become adsorbed on the mineral grain surfaces, as explained by C. F. Bonnet[70] of the American Cyanimid and Chemical Corporation. As a result of this treatment, sand surfaces remain wet with oil though in contact with water, and oil may pass through the pore spaces more readily than water. The productive capacity of a well is greatly diminished by accumulation of paraffin in the pore spaces of the reservoir rock at the wall of the well, and in the screen and liner openings and in the well tubing. An excellent paper by W. Y. Brown[71] of the Carter Oil Company discusses the causes of paraffin accumulation and the mechanical and chemical methods of dealing with this problem.

Flow of Gas-Liquid Mixtures Through Vertical Pipes

Many research projects have had for their objective, a better understanding of the characteristics of flow of gas-oil mixtures in the tubing of flowing and gas-lift wells. Professor R. L. Huntington and S. Cromer,[72] describing a research project conducted at the University of Oklahoma, give the results

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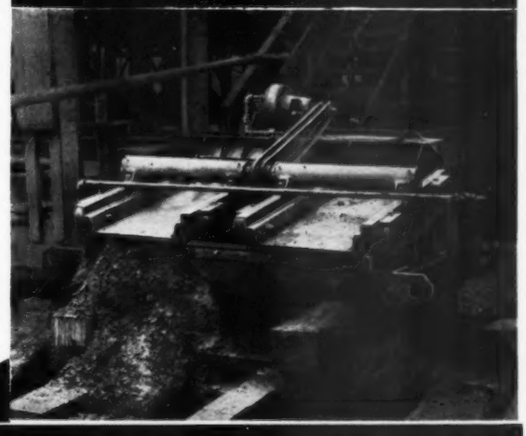

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of visual observations on the flow characteristics of air-water mixtures in a flow column containing transparent glass sections.

Condensate Production

Professor Huntington, in association with R. Ducker,[73] has given the results of studies to determine the extent to which gases tend to become admixed when one gas is forced into sand, the pore spaces of which are filled with another. This research is of particular interest to engineers concerned with gas-injection operations in "distillate fields." A symposium on cycling and condensate production, appearing in the February, 1941, issue of *The Petroleum Engineer,* presents several excellent papers on various phases of this newest phase of the petroleum-producing industry. Professor Huntington[74] and C. Schmidt give the results of laboratory tests indicating that diffusion between injected gas and reservoir gas in recycling operations varies inversely as the pressure. F. H. Dotterweich[75] gives an excellent summary of the present state of development of the scientific background underlying retrograde condensation and related physical properties of hydrocarbon mixtures. S. E. Buckley and J. H. Lightfoot[76] explain the effects of pressure and temperature on condensation of liquid components from a mixture of hydrocarbon gases and vapors. H. S. Gibson[77] of the Anglo-Iranian Oil Company, Ltd., gives results of a field study of closely related subject: the multi-stage separation of gas from crude petroleum as practiced in the Haft Kel field of Persia.

Research on Materials

The petroleum-producing industry annually expends millions of dollars for engineering materials. Realizing the importance of procuring the best material for each use, many oil producers and materials manufacturers have been conducting research having this objective, some of which is currently of great value and interest. The American Petroleum Institute now features a session at each Mid-Year Meeting, at which papers on industrial materials are presented and discussed. At the 1940 Mid-Year Meeting, B. B. Wescott of the Gulf Research and Development Company, C. A. Dunlop of the Humble Oil and Refining Company, and E. N. Kemler of the Gulf Oil Corporation, presented a detailed report on the collapsing strength of well casing and the depths to which casings of different sizes, weights, and materials may safely be carried in oil-field practice.[78] D. R. Dale and D. O. Johnson of the S. M. Jones Company, gave results of laboratory and field endurance tests on sucker rods of various materials.[79] H. W. McQuaid of the Republic Steel Corporation discussed the selection of steel for the manufacture of tools used in the oil-producing industry.[80] In a paper published by the A.I.M.E., H. R. Copson[81] of the International Nickel Company reviewed the results of tests to determine the galvanic corrosion effects resulting from immersion of dissimilar metals in salt-water solutions. *The Journal of the British Institute of Petroleum* features a paper by H. C. H. Darley [82] on the wearing qualities and strength of rotary-drilling hoisting cables. Professor W. H. Carson and E. E. Ambrosius[83] give the results of a program of research conducted under the auspices of the American Society of Mechanical Engineers at the University of Oklahoma, to determine the relative values of different types of meters for measurement of crude petroleum.

Thus, one might continue to note many other worthwhile technical papers that reflect the work done during the last year by research technologists serving the petroleum producing industry; but perhaps enough have been mentioned to indicate the wide range of topics in which our research workers are currently interested. The company and institutional affiliations of the various authors are suggestive of the many different research organizations that are active in this work. The annual cost aggregates millions of dollars; yet it would doubtless seem small in comparison with the ultimate return when measured in terms of increased operating efficiency and reduced production costs that result from it. Probably less than one percent of the gross expenditure of the petroleum producing industry is spent on research. Several times as much could be spent without reaching the economic limit of diminishing returns.

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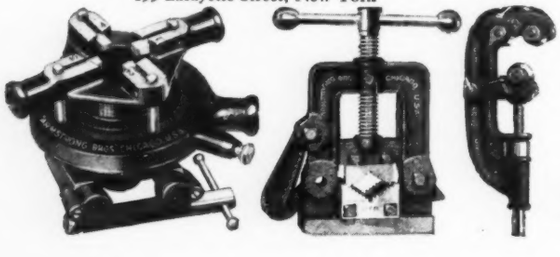

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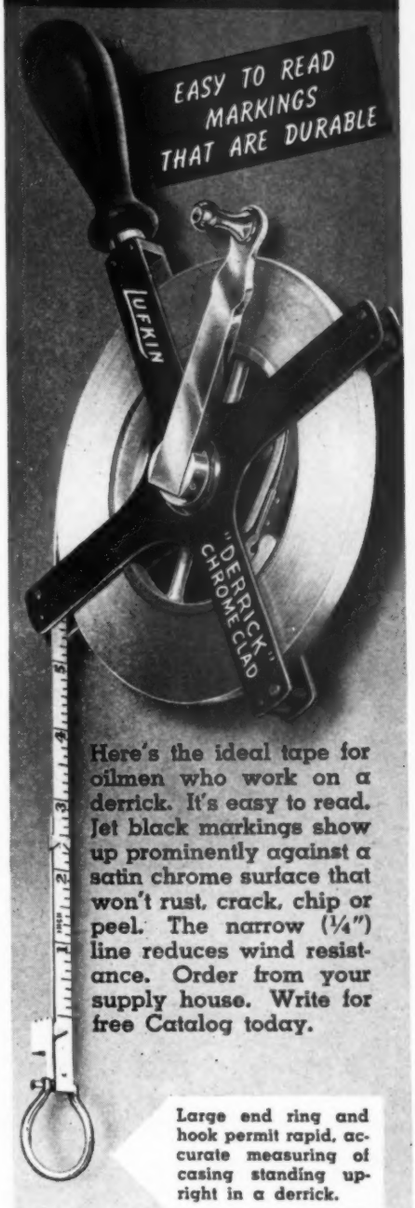

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Draft Standards for Steel Socket-Welding Fittings

A draft of a proposed American Standard for steel socket-welding fittings has recently been completed by The American Society of Mechanical Engineers' Subgroup No. 6 on Welding Fittings of Subcommittee No. 3 on Steel Flanges and Flanged Fittings of Sectional Committee (B16) on the Standardization of Pipe Flanges and Flanged Fittings. This proposal covers overall dimensions, tolerances, and marking for wrought and cast carbon and alloy-steel welding fittings. It is now being distributed to industry for criticism and comment. Copies are available on application. All communications should be addressed to C. B. LePage, assistant secretary, The American Society of Mechanical Engineers, 29 West 39th Street, New York, New York.

The standardization of welding fittings is a part of the project assigned to the Sectional Committee on the Standardization of Pipe Flanges and Fittings (B16) of which Dr. Collins P. Bliss is chairman and J. J. Harman is secretary.

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by Earle Moore

Superintendent, Bell and Loffland, Inc.

EARLE MOORE

superintendent in charge of drilling operations at Wilmington, California, for Bell and Loffland, Inc., drilling contractors operating extensively in California—He went with Little and Bell, the original name of the company, in 1933—During the first few years he worked for the company at Kettleman Hills, Bakersfield, Montebello, Inglewood, Tracy, Taft, and Lost Hills—Four years ago he was placed in charge of the office and field work at Wilmington.

WHEN liquids, such as cement slurry, acid, water, or mud fluid, are pumped down a well to fill a confined space, penetrate into the formation, or wash the hole, there is frequently a definite advantage in knowing to the greatest extent possible what is happening at the subsurface point of operation. A build-up or variation in pressure is probably the most reliable index of what is taking place during actual performance and is often the controlling factor used to indicate a necessary change in, or the end of, the operation. Greater attention is thus being paid to pressure during the job and to pressure records that offer an opportunity to analyze the down-hole performance and provide a history that sometimes proves of value when subsequent work has to be done in the well.

Fig. 1. Chart record of a squeeze-cementing operation

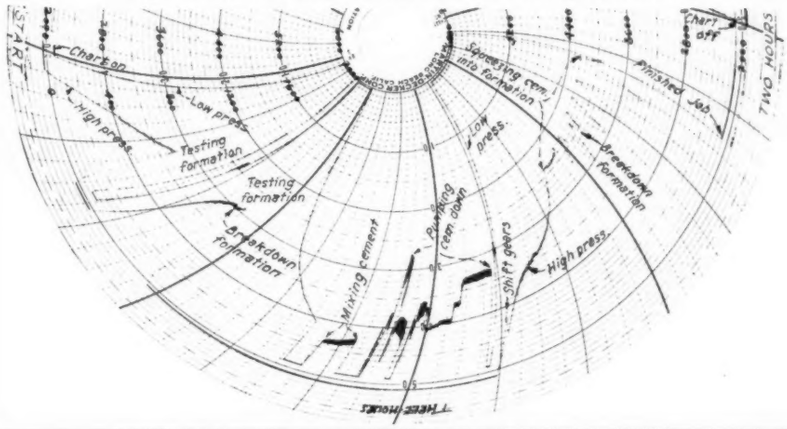
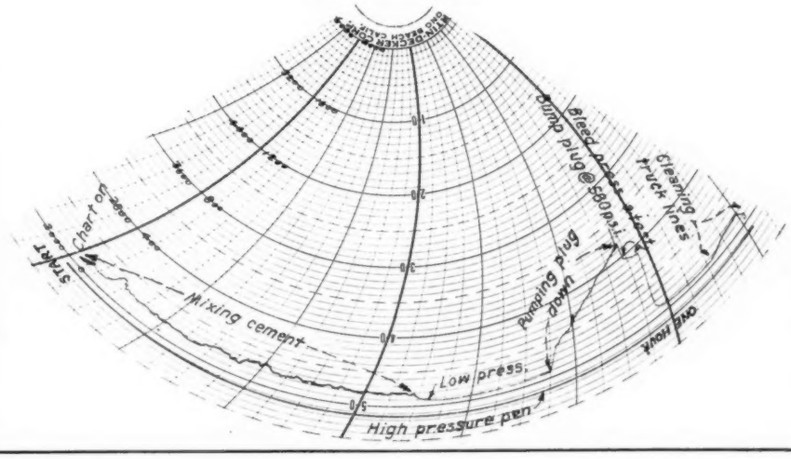


Fig. 2. Most initial casing cementing jobs require only the range of the low-pressure pen



To obtain full value from pressure records, small changes should be readable and it is seldom that a pressure recorder designed to cover the wide range necessary for all types of jobs will clearly define slight variations at low pressures that are frequently required to disclose the true conditions. A pump gauge has therefore been developed that employs two pen arms actuated by a single pressure element.

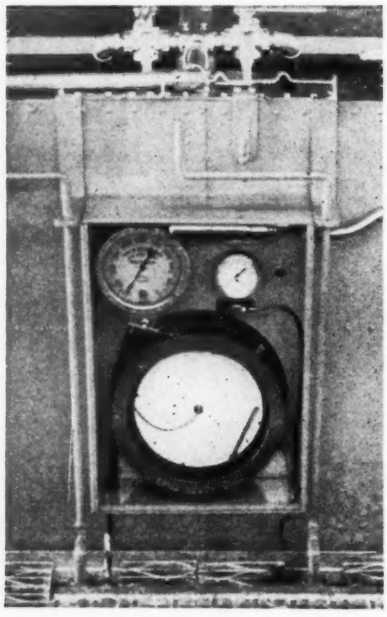
By means of this instrument small changes in pressure over a range of from zero to 2000 lb. per sq. in. are clearly defined by one pen that travels over the full face of the chart. When the pressure exceeds 2000 lb. per sq. in. a second pen takes over and records pressures from 2000 to 6000 lb. per sq. in. One instrument can thus be installed on any cementing or acid truck or otherwise placed in the circulating system to give close readings at lower pressures and then continue to record the higher pressures when the job requires a wide range.

Cementing

The instrument is particularly adaptable to squeeze-cementing operations as shown by the chart record given in Fig. 1.

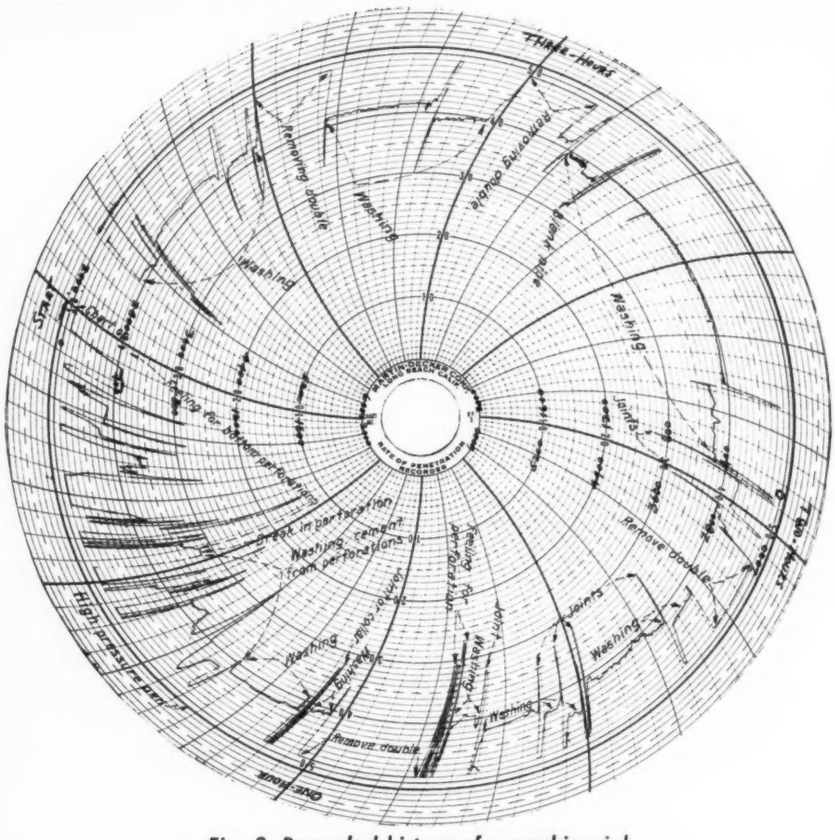
This squeeze job was performed to recement a string of casing at 9275 ft. The operator, first wishing to test the formation, applied pressure to the fluid in the tubing. As shown on the chart, the low-pressure pen immediately climbed to its maximum reading at the center of the chart and the

high-pressure pen then began showing a pressure increase to 3400 lb. per sq. in. At that point the pressure was relieved, causing the high-pressure pen to drop back to 2000 lb. per sq. in. and the low pressure pen to zero. Another test of the formation caused similar action but after exceeding 3600 lb. per sq. in. there was a slight drop in pressure indicating that a formation break-down had occurred and that the formation would take fluid at that pressure of approximately 3600 lb. per sq. in. Pressure was gradually relieved and the cement slurry then mixed as indicated on the chart.



Instrument equipped with separate pens for recording high and low pressures

During mixing and while the slurry was being pumped down, the low-pressure pen recorded the pressure. When pressure was applied to force the cement into place the low-pressure pen moved out to the center of the chart and the high-pressure pen took over. Pressure was slowly built-up until it registered slightly more than 4000 lb. per sq. in. and this pressure was held for a few minutes. Inasmuch as there was no indication that slurry was entering the formation, it was decided to "rock" the slurry by alternately increasing and relieving the pressure. This was done as indicated on the chart until the slurry broke-down the formation as shown. Rocking was continued until 28 sacks of cement had entered the formation at a maximum pressure of 4250 lb. per sq. in. Pressure was then relieved and


Three Hours
Removing double
Washing
Start
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Joint
Washing
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Remove double
Two Hours
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both pens returned to their low-limit positions.

Most initial casing cementing jobs require only the range of the low-pressure pen as shown by Fig. 2, which gives the pressure record while cementing a 10¾-in. water string at a depth of approximately 3000 feet. The chart not only shows the pressure build-up to 580 lb. per sq. in. where the plugs bumped but also records the time consumed in mixing and in displacing the cement slurry.

Washing

Fig. 3 gives the entire history of a washing job by means of which the perforations of a 5-in. prepacked gravel liner were cleaned from depth of 3474 to 3257 feet. The low-pressure pen alone was adequate for recording the pressures employed on this job. It will be noted that the actual washing of the perforations required pressures seldom exceeding 400 lb. per sq. in. but that when blank casing lengths were reached the pressure would increase. Other details of the job are indicated on the chart.

Acidizing

The acid job shown in Fig. 4 required more than the four hours provided on the chart, so the record was allowed to carry over on the same chart until the work was completed. The details of this operation are marked on the record.

The two pens of the recorder are supplied with ink of different colors to distinguish readily the records made by each. Equipped with a semi-automatic stop-and-go mechanism, the clock of the recorder is actuated by pushing a button. The recorder is designed for permanent installation on any type of cementing truck (as shown in the accompanying photograph) or on any portable equipment being utilized for putting fluid down a well under pressures that may be low at one job and high at another, or where both high and low pressures are necessary on the same job.

P 425.218.411

Measuring Particle-Size Distribution and Colloid Content of Oil-Well Drilling Fluids

WHEN clays are mixed with water to make mud fluids for use in drilling wells for oil and gas by the rotary method the liquid mixtures have certain physical characteristics that vary with the quantity and size of their inherent solid particles, says the introduction to Report of Investigation 3549 issued by the U. S. Bureau of Mines. The report was written by George L. Gates and is entitled "Measuring Particle-Size Distribution and Colloid Content of Oil-Well Drilling Fluids." All naturally occurring clays contain variable quantities of particles of different sizes ranging from relatively coarse (sands) through medium (silt) to fine materials of colloidal dimensions. The colloid content is extremely important as a desirable constituent of mud fluids for well drilling. Without colloids the solids in a mud fluid would settle rapidly, and the sealing and wall-building qualities of the fluid would be greatly impaired. Mud fluids with insufficient quantities of colloids also are lacking in "lubricating" qualities, and it is difficult to "run casing" in bore holes drilled with such fluids.

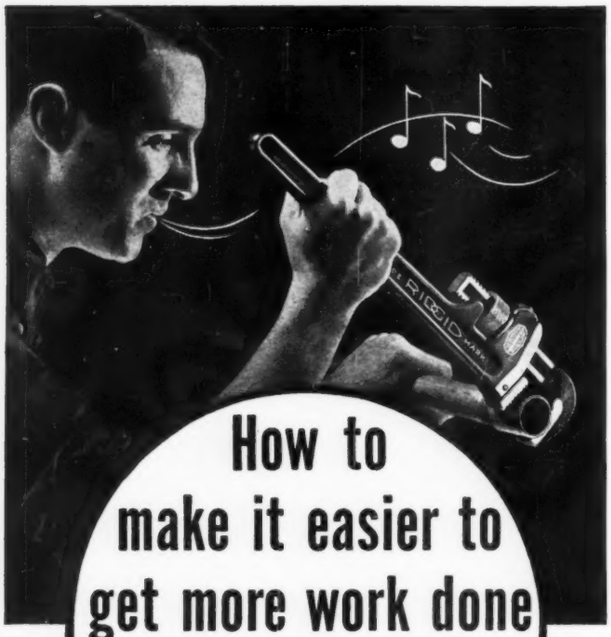
For some time, engineers in the San Francisco laboratory of the U. S. Bureau of Mines have been studying the drilling fluids to ascertain their characteristic properties and to find what constitutes a good mud fluid for use in drilling for oil and gas. In these investigations need developed for a rapid, reliable method for measuring the particle-size distribution and determining the colloid content of mud fluids.

After studying the published methods of particle-size analysis, especially those that have been classified and summarized by Paul S. Roller, the hydrometer method of analysis was selected as that which could most easily be adapted for a study of drilling mud fluids. The hydrometer method requires inexpensive equipment in contrast with other methods of particle-size analysis, and its results compare favorably with those obtained by more direct measurements. In 1927, G. J. Bouyoucos described a hydrometer method for determining the colloid material of soils, and since then the method has been modified slightly by H. H. Hatch, R. C. Thoreen, A. M. Wintermyer, E. A. Willis, and E. E. Bauer. One of the most widely used hydrometer methods of particle-size analysis is the American Society for Testing Materials test for the mechanical analysis of soils (test designation: D422-39).

The method for particle-size analysis described in this report has been found to be comparatively simple and well-adapted to the requirements of the Bureau's studies and is being used to obtain data for a study of possible correlation between particle-size distribution and the other common properties of drilling-mud fluids. It differs from the published methods mainly in the manner in which the sample is prepared for analysis, in the nonuse of a deflocculating agent, in application of a correction factor for dissolved materials that occur in most oil-well drilling-mud fluids, and in measuring the viscosity of the suspension.

In principle the hydrometer method of particle-size analysis consists of sedimentation of the particles, with direct physical measurement of the density of the suspension as a function of time. The rate of settling of particles in the suspension is computed from measurements of the density of the suspension observed at measured depths by means of an hydrometer at definite time intervals.

The method for particle-size determination generally used outside the oil industry, as modified for use in the analysis of oil-well drilling-mud fluids, is described in detail in this report with the thought that the information may prove of value to others engaged in studies of drilling-mud fluids, especially operators of oil-producing properties who are concerned with fundamental methods of testing drilling fluids and the evaluation of materials used in making such fluids.



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by Roy W. Machen

Superintendent, Hamman Exploration Company

ALCHEMISTS of the middle ages were quite frequently troubled with explosions caused by the fire contacting the invisible contents of the vessels they were using. Because they could not understand the reason for these explosions, they thought they were caused by the presence of evil spirits. The early scientists thought that gas as such was permanent in state and that it was impossible to reduce it to any other state. We know today, however, that all gases can be liquefied by the application of pressure at reduced temperatures.

It is known that the pressure of a gas depends on the temperature. If the temperature of a gas is continuously increased, it will become necessary to increase the pressure continuously to begin condensation. If the temperature is increased enough, however, the pressure exerted on the gas, no matter how great, will be insufficient to induce condensation. Thus a reduction in temperature is often the easiest method of obtaining a condensate. The critical temperature for a specific gas is that temperature above which it is impossible to liquefy that gas, irrespective of the pressure imposed. The vapor pressure of the gas at its critical temperature is termed the critical pressure. The condition of a gas at its critical temperature and pressure is a phenomenon similar to the equilibrium conditions that exist when at any definite temperature a liquid exerts a vapor pressure on its containing vessel such that the amount of liquid vaporizing is equivalent to the amount of vapor that is condensing. In fact, it may be stated that at critical temperature and pressure the separation between gas and liquid is indefinite and that the gas and liquid are identical. The critical temperature of methane, CH_4, is minus 115°F., and the critical pressure is 51 atmospheres or 750 lb. per sq. in. absolute. These figures mean literally that at any temperature below minus 115°F. methane can be liquefied by pressure alone, but at any temperature above minus 155°F. methane cannot be liquefied by the exertion of any amount of pressure; furthermore, at 115°F. the vapor pressure of methane is 750 lb. per sq. in. abs.

ROY W. MACHEN

received a bachelor's degree from Oklahoma City University in 1927—Employed for six and one-half years by the Peppers Gasoline Company as refinery clerk, refinery and gasoline plant chemist, and gas engineer—Later saw service with various independent refining companies as gas engineer, operator in high-pressure gasoline plants, refinery construction engineer, and superintendent of refinery operations—Now is superintendent for the Hamman Exploration Company—Is a registered petroleum and natural gas engineer.

Although methane cannot exist as a liquid above its critical temperature when in the pure state, it can exist in solution as a liquid at temperatures considerably higher than its critical temperature. Thus, methane, ethane, propane, and butane, all normally gases at normal atmospheric temperatures and which exist as such in natural gas, can be absorbed in an oil and exist in liquid form at temperatures that are somewhat higher than the boiling points of the pure constituents.

The essential physical properties governing flow of gases and liquids are similar and for that reason both are considered as fluids by the scientist.

The tendency of a gas to expand indefinitely so that it completely fills its containing vessel uniformily is perhaps its most striking characteristic.

If one gas is liberated in a vessel that already contains another gas, the former, regardless of the fact that it is lighter or heavier than the latter, and regardless of the position of entrance into the vessel, whether above or below the latter, will slowly distribute itself through the latter gas. This spread of one gas throughout the body of the gas already present is called diffusion and eventually the two gases become evenly mixed. Irrespective of the fact that one gas may be lighter or heavier than the other, the two will not stratify as they are brought together in the same container nor will they separate into layers or strata after having once been mixed.

The compressibility of gases is a third important characteristic. A volume of gas will change materially with only a slight change in pressure.

Because of these characteristics numerous gas laws have been formulated and standard conditions of measurement set. Some of these laws are subject to much correction as they are applied to various gases whereas others are accepted as accurate for all gases and conditions of state.

The unit of measurement used in describing definite volumes of gas is the cubic foot. The standard temperature base generally used in correcting gas volume in the plant is 60°F. The pressure base to which gas volumes are corrected will vary, depending on location of the plant and gas contract provisions. The pressure base most generally used, however, is termed the 4-oz. base and is 14.65 lb. per sq. in. abs. (14.4 plus 4/16 or 0.25 lb. per sq. in.)

The Gas Laws

All gases are composed of small units or particles called molecules. These molecules are infinitely small. A volume of gas the size of a pin head might contain millions of molecules. These molecules move about, continuously at

work, striking against one another, rebounding from the sides of the vessel containing them, and delivering a bombardment of impacts, the force of which depends upon their velocity. The phenomenon of gas pressure is due to this continuous attack by the molecules. This explanation of the behavior of gases is called the kinetic theory.

Avogadro, after long and careful study, by chemical considerations arrived at the conclusion that when the same conditions of temperature and pressure exist, equal volumes of all gases contain the same number of molecules. Avogadro's law of gases is technically not a law at all, but rather a hypothesis or theory. It has been proved in numerous cases, however, examples of which are methane and carbon dioxide, to be a basic principle to be considered in making gas calculations.

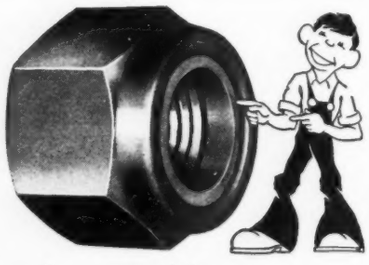
Molecular Weight

A unit of molecular weight of any gas when expressed in grams will occupy 22.4 liters at 0°C. and 760 mm. Hg. pressure. If the molecular weight is expressed in terms of the English system, i.e., in pounds, the volume would be 359 cu. ft. at 32°F., when at atmospheric pressure. This means that no matter what gas it is, a mol of gas (one molecular weight of a gas) is 359 cu. ft. when the gas is at a temperature of 32°F. and under 14.7 lb. abs. pressure. This same definition for a mol holds true for either pure gases or mixed gases that are composed of any number of components. For example, each 1000 cu. ft. of gas coming into the plant at 32°F. and 14.7 lb. abs. is equivalent to 1000/359 or 2.785 mols. Inasmuch as the plant volumes are corrected to 60°F. and 14.65 lb. pressure, 359 cu. ft. must be converted to the volume corresponding to this temperature and pressure. This value is found to be 380 cu. ft. The value of one mol of gas, therefore, at 60°F. and 14.65 lb. abs. is 380 cu. ft.

By Avogadro's hypothesis, equal volumes of gas at the same temperature and pressure contain equal numbers of molecules. The weights of the various gases for equal volumes must, therefore, be in proportion to the weights of the various molecules that compose them. For instance, if one gas weighs 6 times more than another gas of equal volume, this difference in weight is caused by the fact that the molecules of the first gas are 6 times heavier in aggregate than are those of the latter gas. The value of 32 has been arbitrarily assigned to oxygen as the molecular weight of that gas. The molecular weights of all the other substances are given weights, or values, that are related to the value assigned to oxygen in the same ratio as their gases are related in weight to that of oxygen. Thus, if a volume of a compound is three times as heavy as an equal volume of oxygen, the molecular weight would be three times 32 or 96. In the same way, if the weight of the compound had been only half the weight of an equal volume of oxygen, the molecular weight would have been only 16. When speaking of molecular weights in terms of the English system of measurements, the value is expressed in pounds, for example, the molecular weight of oxygen is 32 lb.

The molecular weights of the hydrocarbons found in natural gas are as follows:

Methane, CH_4	16.03
Ethane, C_2H_6	30.05
Propane, C_3H_8	44.06
Butane, C_4H_{10}	58.08
Pentane, C_5H_{12}	72.10
Hexane, C_6H_{14}	86.11
Heptane, C_7H_{16}	100.13
Octane, C_8H_{18}	114.14
Nonane, C_9H_{20}	128.16
Decane, $C_{10}H_{22}$	142.18



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As was stated in a previous article,[1] the empirical chemical formulas of hydrocarbons may be used as bases for calculating the molecular weights if the atomic weights of the constituents of the compound are substituted. The molecular weight of n-decane by calculation would be as follows:
n-decane, $C_{10}H_{22} = 12 \times 10 + 1 \times 22$ or 142.

Mol Fraction and Mol Percent

Many times it is desired to express the composition of a gas in terms of mol fraction or mol percent rather than in weight fraction or weight percent. This is quite easily done as the mol fraction of any particular component is the number of mols of that component divided by the total number of mols in the mixture. The sum of the mol fractions of all of the components must equal unity. Mol fraction multiplied by 100 is equal to mol percent.

In the reporting of the constituents of a gas, the method of expression is usually volume percent. If a comparison is made of gas volume percent and mol percent it will be found that they are identical in value.

[1] "Review of Basic Physical and Chemical Laws That Govern Gasoline Plant Operation," by Roy W. Machen. *The Petroleum Engineer*, December, 1940.

For instance, a gas was reported as shown in Table 1 and it is desired to convert the given figures in volume percent to mol percent:

TABLE I

Component	Gas volume, percent	Volume, cu. ft. per 100 cu. ft. of mixture	Mol fraction	Mol percent
Methane	84.48	84.48	0.8448	84.48
Ethane	7.75	7.75	0.0775	7.75
Propane	3.89	3.89	0.0389	3.89
*Iso*Butane	1.72	1.72	0.0172	1.72
n-Butane	1.23	1.23	0.0123	1.23
*Iso*Pentane	0.43	0.43	0.0043	0.43
n-Pentane	0.28	0.28	0.0028	0.28
Hexanes plus	0.22	0.22	0.0022	0.22
	100.00	100.00	1.0000	100.00

Given the gas volume percent, for any quantity of gas, the volume of any constituent is equal to the given quantity multiplied by the percentage of that constituent present. Using methane in Table I as an example:

$$\frac{84.48 \times 100}{100} = 84.48 \text{ cu. ft.}$$

As the mol fraction is equal to the number of mols of any one constituent divided by the total number of mols in the volume, the number of cu. ft. in the mixture of any one component divided by the total number of cu. ft. in the mixture will also give mol fraction. Using methane again as an example: The number of cu. ft. of methane present in the 100 cu. ft. of gas in question is 84.48. Then, 84.48 divided by 100 is equal to the mol fraction of methane or 0.8448.

As the mol percent of any component present is the mol fraction multiplied by 100, the mol fraction of methane, 0.8448 multiplied by 100 is equal to 84.48, or the same value as originally given in the reported analysis as gas volume percent.

The number of mols of each component present at base temperature and pressure can be found by dividing the number of cu. ft. of each component present by 380, or as in the case of methane, 84.48/380 = 0.2223 mol.

In the study of gases we find that mol percent and gas volume percent are equal one to the other. This is not

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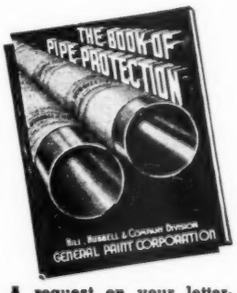

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true, however, in the case of a liquid. The liquid volume percent and mol percent are not the same. The procedure for the determination of mol percent when the analysis is presented in liquid volume percent is tabulated in Table 2.

TABLE 2

Constituent	Liquid volume, percent	Lb. per gal.	Weight, lb.	Molecular weight, lb.	Mols	Mol fraction	Mol percent
Propane	0.73	4.30	3.139	44.06	0.0712	0.0125	1.25
*Iso*Butane	1.77	4.69	8.301	58.08	0.1429	0.0251	2.51
n-Butane	2.28	4.85	11.06	58.08	0.1904	0.0334	3.34
*Iso*Pentane	3.29	5.22	17.17	72.10	0.2381	0.0418	4.18
n-Pentane	2.72	5.27	14.33	72.10	0.1988	0.0349	3.49
Hexanes plus	89.21	6.21*	554.0	114.00*	4.860	0.8523	85.23
	100.00				5.7014	1.0000	100.00

*Assumed value based on specific gravity of hexanes plus.

The table is made up as follows: The liquid volume percent is given and this value times the weight of the fraction in lb. per gal. gives the number of lb. per 100 gal. The number of lb. per 100 gal. divided by the molecular weight gives the number of mols per 100 gal. The mol fraction of each component is found by dividing the total number of mols into the number of mols of the component contained in the mixture. The mol percent is then the mol fraction multiplied by 100.

Boyle's Law

The manner and rate of pressure change due to the expansion or compression of gases was first studied by Boyle. He succeeded in the establishment of a general law that is now known as Boyle's Law; i.e., if the temperature is kept constant, the volume that a given mass of gas will occupy is inversely proportional to the absolute pressure. In other words, if a gas measured at one atmosphere absolute pressure is found to occupy 10 cu. ft. and it is then compressed to two atmospheres absolute pressure it will occupy only 5 cu. ft. If this same mass of gas is further compressed to four atmospheres abs. pressure it will occupy only one-fourth the original space, or 2.5 cu. ft., provided, of course, the temperature has remained constant during each compression. In the same way, if 10 cu. ft. of gas at 40 lb. per sq. in. abs. is released so that the pressure is only 20 lb. per sq. in. abs., the volume of gas will be double the original volume or 20 cu. ft.

If we let P = the pressure (absolute)
V = the volume at that pressure

$$PV = 40 \times 10 \text{ or } 400$$
$$P_1V_1 = 20 \times 20 \text{ or } 400$$

We can now express Boyle's Law in another manner, that is, the pressure times the volume is a constant. By letting K equal a constant, we can set up the law in formula form: $PV = K$

As we have found the constant, K, to be the same for different pressures and volumes, $PV = P_1V_1 = P_2V_2 = P_3V_3$, etc. $= K$

Given 380 cu. ft. of gas at 14.65 lb. per sq. in. abs. and required to find the volume at 60 lb. per sq. in. abs., we have (by substituting the proper values in the formula, $PV = P_1V_1$) $14.65 \times 380 = 60 \times V_1$

$$V_1 = \frac{14.65 \times 380}{60} = 92.78 \text{ cu. ft.}$$

Like many other laws of science, Boyle's Law is only an approximation as it holds true for only perfect gases, and is not exactly true when applied

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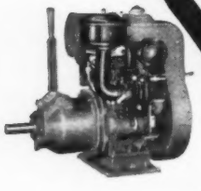

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to any actual gas. So long as the pressure for which calculations are made does not pass 200 lb. per sq. in. abs., however, the direct application of Boyle's Law will not involve any serious error. Many engineers, however, make no correction and handle heavy vapors and higher pressure calculations by direct application of Boyle's Law because no other convenient law is available.

Charles' Law

The effect on gas volumes due to changes in temperature is described by Charles' Law. Simply stated, this law is: the volume varies directly with the absolute temperature, provided the pressure remains constant. If we had 100 cu. ft. of gas at 150° absolute temperature and 50 lb. absolute pressure and the pressure remained constant as the temperature was increased to 300° absolute, the volume of gas would increase to 200 cu. ft., or twice its original volume. If the absolute temperature was increased to 600° and the pressure remained constant, the volume of gas would then be 400 cu. ft., or twice the volume at 300° absolute.

Quantitative experimentation long ago proved that the effect of temperature on different gases was the same. It was found that the volume of gases increased or decreased 1/273 of its volume at 0°C. for each degree increase or decrease from 0°C. Obviously, if the temperature of a gas was brought to minus 273°C. it would be expected that the volume would be zero. This is possible with a perfect gas, but with actual gases, condensation takes place long before that temperature is reached. One of the most difficult gases to condense, helium, whose condensation point is minus 451°F., would not be a gas at minus 273°C. This temperature, minus 273°C., is called absolute zero. The corresponding reading on the Fahrenheit scale is minus 459.6° or roughly minus 460°F.

The absolute temperature scale on which minus 273°C. is zero is known as the Kelvin Scale, or °K.

The absolute temperature scale on which minus 460°F. is zero is known as the Rankine Scale, or °R.

To find the degrees absolute Fahrenheit or Centigrade, the following relationship may be of advantage:
Degrees absolute Fahrenheit + 460 = degrees Rankine (°F + 460 = °R).
Degrees absolute Centigrade + 273 = degrees Kelvin (°C + 273 = °K).
1°R = 1.8°K.

The changes occurring in a volume of a gas when the pressure is held constant and the temperature is varied have been found to be directly proportional to the change in absolute temperature. Also, it has been found that if the pressure is permitted to change at the same time the temperature changes and the volume is held constant, the corresponding change in pressure is in direct proportion to the absolute pressure.

If we know the volume of gas at one temperature and pressure and want to know the volume at another temperature and the same pressure, we may do so by means of the equation: $V_1T_2 = V_2T_1$

If we know the pressure at one temperature and the pressure at another temperature is desired, the volume being held constant, the equation, $P_1T_2 = P_2T_1$, should be used, in which:

V_1 = known volume
T_1 = absolute temperature of known volume (or pressure)
V_2 = unknown volume
T_2 = absolute temperature of unknown volume (or pressure)
P_1 = known pressure
P_2 = unknown pressure

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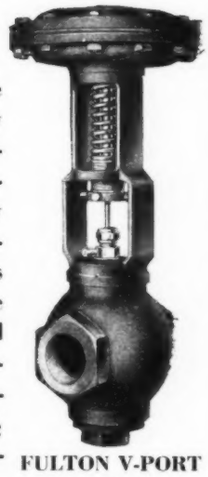

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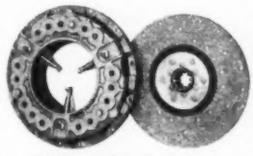

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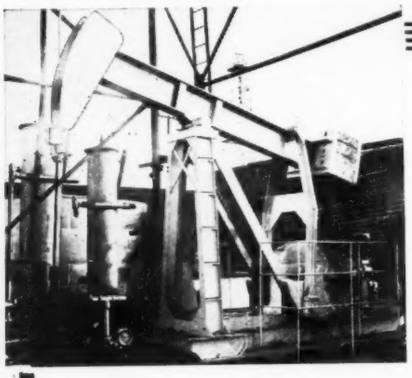

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New Petroleum Engineering Building For University of Texas

The University of Texas recently had what it hopes will prove to be a foundation for national leadership in the production of young petroleum engineers. The occasion was the cornerstone laying of the new $200,000 petroleum engineering building, to open next fall as one of the nation's best laboratories for turning out experts in the field of petroleum.

Formal dedication of the building will be observed early this fall, Harry H. Power, petroleum engineering chairman, said.

Three stories high and 175 ft. long, the building spreads, in simple factory style architecture, over 33,000 sq. ft. of floor space.

Cotton Valley Plant to be Dedicated July 10

On Thursday, July 10, the recently completed Cotton Valley cycling and pressure maintenance plant in the Cotton Valley field, Webster Parish, Louisiana, will be formally dedicated at an all-day barbecue and ceremony, according to announcement of J. R. Butler, general manager, Cotton Valley Operators Committee. The principal speaker will be Governor Sam Houston Jones of Louisiana. The governor has definitely stated he will be in attendance and Major B. A. Hardey, chairman of the Board of Minerals; Joseph L. McHugh, director of the Department of Minerals; Geo. A. Wilson, attorney for the Department of Minerals, and other public officials will be present.

Arrangements are now being made for the dedicatory ceremonies to be broadcast over one of the Shreveport radio stations.

All Cotton Valley operators and royalty owners and their families and guests and friends are invited and a crowd of perhaps 1000 is expected. The governor's party will be conducted on an official tour of the plant. A barbecue lunch will be served by the Cotton Valley Operators Committee employees in the park.

The Cotton Valley unitization and pressure-maintenance project, recognized in the industry as one of the outstanding conservation and unitization achievements of the Mid-Continent fields, was culminated by the recent completion of the plant at a cost in excess of $2,250,000.00. This plant will handle 150,000,000 cu. ft. or more of gas per day. Distillate production is expected to be about 10,000 bbl. per day, and in excess of 500 bbl. daily of *iso*butane will be manufactured. Residue gas of about 130,000,000 cu. ft. daily from the plant will be returned to the producing formation through injection wells. The entire field comprising approximately 12,000 acres has been unitized, as to all formations below the base of the Travis Peak, under the terms of the Cotton Valley Unitization and Pressure Maintenance Agreement executed by 26 operators, independents and majors, and more than 600 land owners and royalty owners. After public hearings before the Department of Minerals an order was issued approving the agreement, designating the Cotton Valley Operators Committee as the operator of the unitized properties and providing for the field to be operated as a unit. Gas distillate production is from wells in the Bodcaw and "D" sands found at a depth below 8000 ft. with gas-distillate ratios of approximately 13,000 to 1, and the gas distillate area is encircled by a rim of oil wells, located outside the Bodcaw and "D" sand participating areas, producing with gas-oil ratios varying from 2000 to 1 upwards. One of the chief conservation features of this operation is the handling of the rim oil gas production in the plant, thus utilizing this gas for return to the formation, for pressure maintenance, and sale for industrial and commercial purposes.

MEETINGS

American Chemical Society—September 8, 9, 10, 11, and 12, Atlantic City, New Jersey.

National Petroleum Association, Annual Meeting—September 17, 18, and 19, Hotel Traymore, Atlantic City, New Jersey.

West Virginia Oil and Natural Gas Association, Annual Convention—October 2 and 3, Clarksburg, West Virginia.

Texas Mid-Continent Oil and Gas Association, Annual Meeting—October 9, 10, and 11, Beaumont, Texas.

American Association of Petroleum Geologists—October 16 and 17, Los Angeles, California.

American Institute of Mining and Metallurgical Engineers, Petroleum Division—October 16, 17, and 18, Dallas, Texas.

Independent Petroleum Association of America, Twelfth Annual Meeting—October 20, 21, and 22, Tulsa, Oklahoma.

American Institute of Mining and Metallurgical Engineers, Petroleum Division—October 30 and 31, Los Angeles, California.

California Natural Gasoline Association—October 31, Los Angeles, California.

American Petroleum Institute, 22nd Annual Meeting—November 3, 4, 5, 6, and 7, San Francisco, California.

New Mexico Oil and Gas Association—December 3, Artesia, New Mexico.

Oklahoma Stripper Well Association—December 5, Tulsa, Oklahoma.

American Institute of Electrical Engineers, Southeastern District—December 3, 4, and 5, New Orleans, Louisiana.

Texas Oil and Gas Association—February 28, 1942, Wichita Falls, Texas.

International Petroleum Exposition—May 16, 17, 18, 19, 20, 21, 22, and 23, 1942, Tulsa, Oklahoma.

J. R. Spence Made General Sales Manager Stoody Company

J. R. Spence has recently been appointed general sales manager of Stoody Company. Spence has been active in the hard-facing industry for many years and is not only responsible

J. R. SPENCE

for the development of several hard-facing alloys, but has also been instrumental in determining correct procedures for hard-facing many types of industrial equipment.

Spence has been with Stoody Company more than six years, serving first as chief metallurgist and later as industrial sales and research manager.

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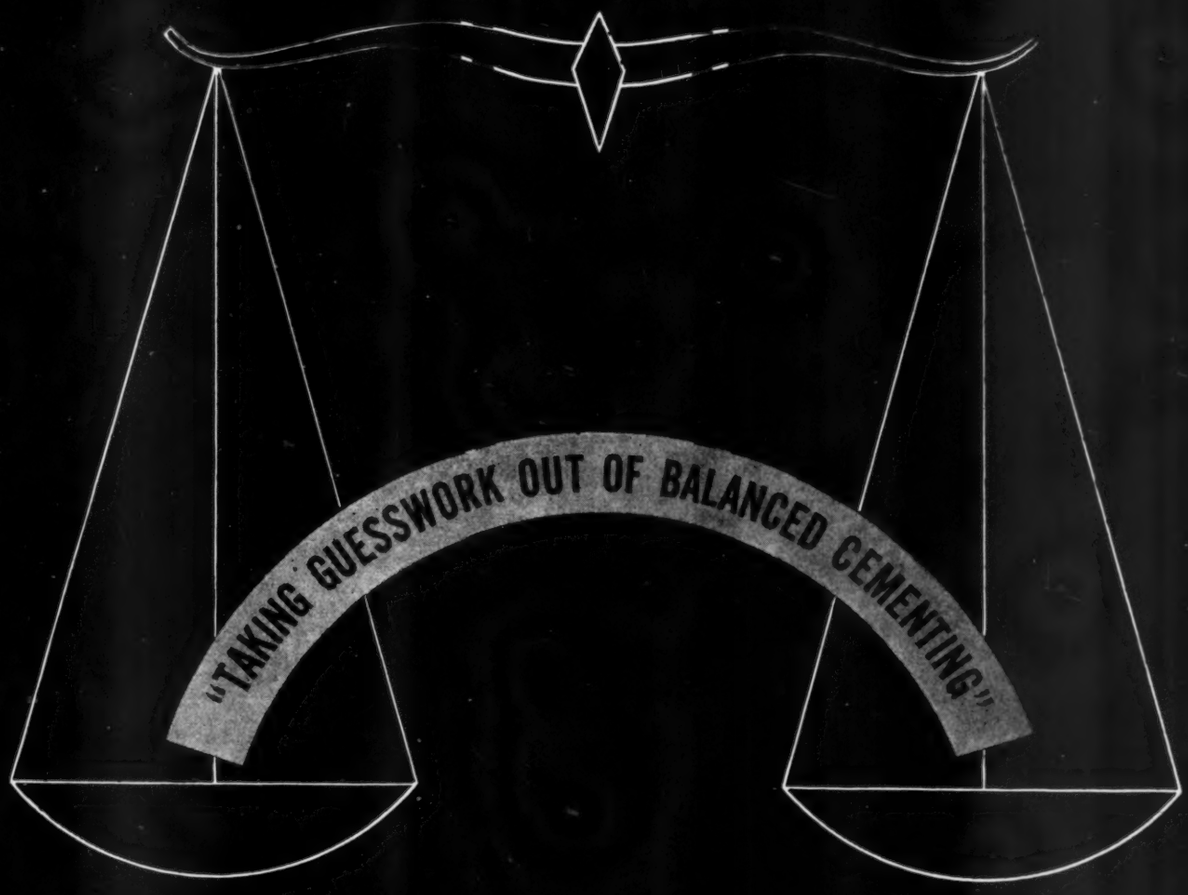

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